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Use of Cranes in System Dynamics and Controls Education

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Abstract: Cranes provide an excellent platform for teaching system dynamics and controls. Cranes have a simple pendulum-type oscillation that is useful for demonstrating basic ideas. Cranes also have additional dynamic effects such as motor dynamics, velocity limits, payload variations, and nonlinear slewing dynamics that make them well suited for advanced study. If the cranes are made remotely operable, then students can also study tele-operation and control of systems with time delays. System dynamics and control courses taught at the Georgia Institute of Technology utilize cranes in both the lecture and laboratory exercises. The primary goal of using the cranes is to provide hands-on experiences in system dynamics and implementation of controllers on real systems. This paper describes the cranes and the complementary curriculum.

Keywords: Crane Control, Oscillation, Vibration, Input Shaping, Engineering Education

1. INTRODUCTION

System dynamics and controls education is often filled with extensive theoretical development and complicated mathematics. Therefore, students often lose sight of the practical applications of the material. The use of complementary laboratory exercises can alleviate this problem. However, this introduces an additional challenge to professors, who must develop lab exercises that reinforce lecture material. They must also build and maintain experimental setups that are robust to mistreatment and instability.

Cranes are excellent testbeds because crane payload oscillation is a problem that all students can immediately see and understand. While there are numerous types of cranes, all have an overhead support point that moves around a suspension cable that lifts the payload. Moving the overhead support point, such as the trolley of a bridge crane, is fairly straightforward; however, moving the suspended payload in a controlled manner is quite challenging. Beyond the basic pendulum mode, cranes also have additional dynamic effects such as motor dynamics, velocity limits, and nonlinear payload dynamics that make them well suited for both introductory and advanced study.

Although cranes have many interesting dynamic properties, the primary challenge is to control payload oscillation. Therefore, all crane-based curriculum has this as a primary component. Two main control approaches can be used to reduce payload oscillation: feedback control and command shaping. Feedback control is easily achieved for the overhead support point, but it is difficult to use for payload control because accurate sensing of the payload oscillation is difficult to achieve. Command shaping does not require sensors. It reduces oscillations by filtering out vibration-inducing components from the command signal. This modification is accomplished by convolving the original command signal with a sequence of impulses [Smith, 1958, Singer and Seering, 1990]. The result of the convolution is then used to drive the crane motors. This input-shaping process is demonstrated in Fig. 1. Several variations of this idea have been developed for crane control [Starr, 1985, Singer et al., 1997, Parker et al., 1999, Khalid et al., 2006, Singhose et al., 2007, Sorensen et al., 2007b].

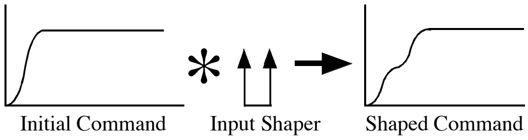


Fig. 1. The Input Shaping Process

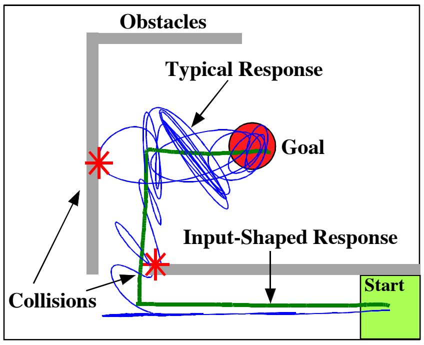


Fig. 2. Typical Payload Responses

Figure 2 compares the responses of the crane payload of the 10-ton bridge crane shown in Fig. 3 for a typical maneuver under standard operation and when input

Fig. 3. 10-Ton Bridge Crane at Georgia Tech

shaping is enabled. The two responses are from the same human operator. The figure shows that under normal operation the payload has large oscillations. These oscillations are virtually eliminated by input shaping. Such dramatic performance improvement motivates students to understand the control system, especially when they are the ones driving the crane. Input shaping also proves a worthwhile contrast to the feedback methods taught in controls coursework and allows illustrative comparisons between open and closed-loop control methods.

The next section describes four cranes that have been built at Georgia Tech for research and educational purposes. Section 3 describes how crane-based homework, simulations, and laboratories have been integrated into the curriculum. Section 4 discusses use of the cranes in international collaborations. The use of the cranes for undergraduate research projects is described in Section 5.

2. CRANE LABORATORY FACILITIES

2.1 10-Ton Industrial Bridge Crane

The crane shown in Fig. 3 has a workspace of 6 meters high, 5 meters wide and 42 meters long. Signals generated by the human operator travel from the control pendant to the bridge-and-trolley control box, where a Siemens programmable logic controller (PLC) performs feedback control and input-shaping. The resulting commands are then sent to the trolley and/or bridge Siemens Masterdrives motor drives. The crane is also equipped with a Siemens vision system to measure payload response.

2.2 Portable Bridge Crane

A small, transportable bridge crane is shown in Fig. 4 [Lawrence and Singhose, 2005]. One purpose of this crane is to provide a hands-on learning tool for students outside Georgia Tech that cannot use the 10-ton crane. The crane was transported to Georgia Tech Lorraine in France during the fall of 2004. In the spring of 2006, it was used in an Atlanta-area high school.

The portable bridge crane is approximately one cubic meter in volume. It is driven by Siemens AC synchronous servomotors, which move the trolley and bridge axes via two timing belts. A direct-drive DC motor is used for hoisting. A Siemens digital camera is attached to the trolley to measure the payload swing. Signals from the control pendant are sent to a Siemens PLC that generates a series of velocity setpoints for the motors.

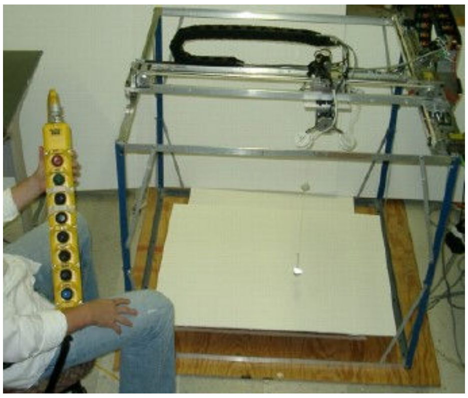
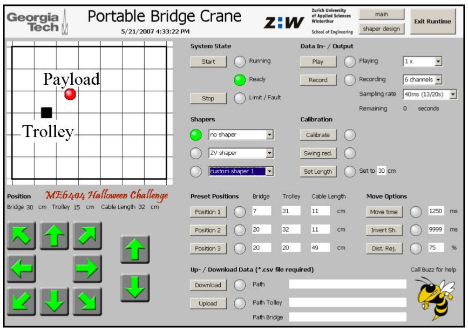


Fig. 4. Portable Bridge Crane



5/21/2007 4:33:22 PM

Position
Bridge 30 cm Trolley 15 cm Cable Length 32 cm

1 x
6 channels
Sampling rate 40ms (13/20s)
Remaining 0 seconds

● no shaper
○ ZV shaper
○ custom shaper 1

Set to 30 cm

Preset Positions	Bridge	Trolley	Cable Length	
Position 1	7	31	11	cm
Position 2	20	32	11	cm
Position 3	20	20	49	cm

Move Options		
Move time	1250	ms
Invert Sh.	9999	ms
Dist. Rej.	75	%

Fig. 5. Bridge Crane Computer Interface

The portable bridge crane has tele-operation capabilities that allow it to be operated in real-time from anywhere in the world via the internet. To achieve tele-operation, the controlling PC was equipped with UltraVNC. When operated remotely, the crane is driven using the Graphical User Interface (GUI) shown in Fig. 5. Local users also have the option of using this interface to control the crane. The upper left portion of the screen shows a real-time animation of the crane from an overhead view using the camera and encoder data. The square is the trolley position and the circle is the payload position. The crane can be driven manually, using the directional arrows at the bottom left of the screen, or using stored velocity setpoints that are executed with the "Play" button.

2.3 Portable Tower Crane

A small, transportable tower crane, shown in Fig. 6, has also been constructed [Lawrence et al., 2006b]. The crane is approximately 2m tall with a 1m jib arm. The crane has three degrees-of-freedom actuated by Siemens synchronous AC servomotors. The slewing axis is capable of 340° rotation. The trolley moves radially along the jib via a lead screw, and a hoisting motor controls the suspension cable length. A Siemens digital camera is mounted to the trolley and records the swing deflection of the payload. This crane also has tele-operation capabilities similar to the portable bridge crane.

The PLC can receive velocity commands from either a control pendant or a PC. The PC controls the crane using the GUI shown in Fig. 7. The upper left portion of the screen shows a real-time animation of the crane from an overhead view using the camera and encoder data. The square is the trolley position and the circle is the payload position. The current configuration is also numerically

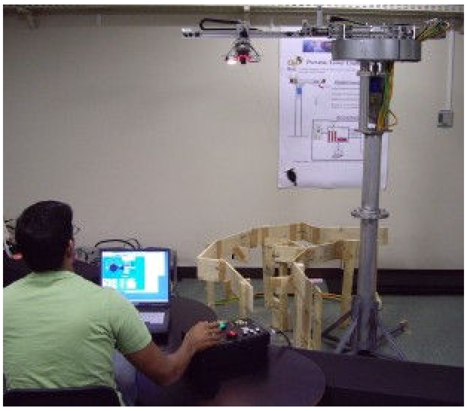
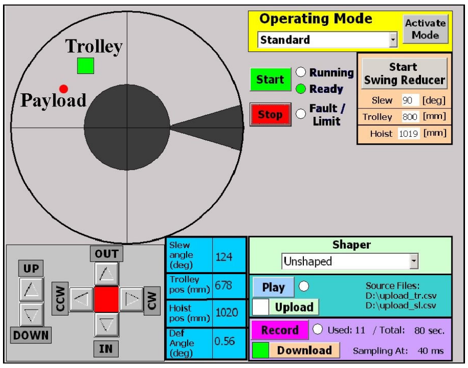


Fig. 6. Portable Tower Crane



Operating Mode: Standard

Slew 90 [deg]
Trolley 800 [mm]
Hoist 1019 [mm]

Slew angle (deg)	124
Trolley pos (mm)	678
Hoist pos (mm)	1020
Def Angle (deg)	0.56

Shaper: Unshaped

Source Files:
D:\upload_tr.csv
D:\upload_sl.csv

Used: 11 / Total: 80 sec.
Sampling At: 40 ms

Fig. 7. Tower Crane Computer Interface

displayed in the bottom center of the display (slew angle, trolley pos, etc.). The crane can be manually driven using the directional arrows at the bottom left of the screen. In addition, velocity setpoints can be stored and then executed with the "Play" button.

2.4 Mobile Boom Crane

A small-scale, mobile boom crane, modeled in Fig. 8, is currently under construction. The crane has a 2m boom capable of luffing from 10° to 90° and slewing 300°. The crane is mounted on a rear-wheel drive mobile base with a front-wheel rack-and-pinion steering system. All five degrees-of-freedom are actuated by Siemens AC Servomotors. Like the portable bridge and tower cranes, the boom crane will be capable of being remotely controlled via the Internet.

All of the electronics, including the power conversion, PLC, and motor drives are mounted on board, allowing the crane to operate with only a power cable tethered to the ground. This allows for the crane to be easily tested on all types of terrains outside of a laboratory setup. The oscillation of the payload is measured by a Siemens camera mounted at the tip of the boom. The orientation of the camera is maintained by a four-bar mechanism.

Two interfaces have been designed to control the crane. The first is a wireless joypad, capable of actuating all degrees-of-freedom, as well as other functions such as controller selection. The wireless capability will be useful when making use of the crane's mobile base. The second control interface is the GUI shown in Fig. 9. The upper left corner of the interface is an overhead view crane and payload. This orientation is used to determine the cranes slewing position as well as the payload's swing. The bottom left corner shows a side view of the crane, showing the luffing position of the crane. The controls for the crane are in the top middle of the interface. Advanced options such as input-shaping control, data recording, and trajectory playback can be edited in the bottom right of the interface.

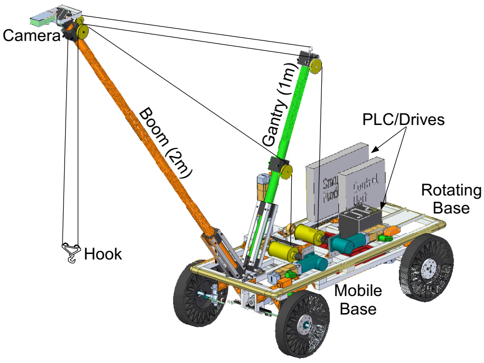
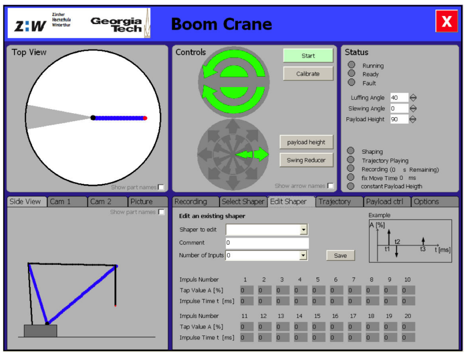


Fig. 8. Sketch of Mobile Boom Crane



○ Running
○ Ready
○ Fault

Luffing Angle 40
Slewing Angle 0
Payload Height 90

○ Shaping
○ Trajectory Playing
○ Recording (0 s Remaining)
○ fix Move Time 0 ms
○ constant Payload Heigth

Edit an existing shaper

Shaper to edit
Comment 0
Number of Inputs 0

Impuls Number	1	2	3	4	5	6	7	8	9	10
Tap Value A [%]	0	0	0	0	0	0	0	0	0	0
Impulse Time t [ms]	0	0	0	0	0	0	0	0	0	0
Impuls Number	11	12	13	14	15	16	17	18	19	20
Tap Value A [%]	0	0	0	0	0	0	0	0	0	0
Impulse Time t [ms]	0	0	0	0	0	0	0	0	0	0

Fig. 9. GUI of Mobile Boom Crane

Two network cameras used for observation of the crane are also accessible on the interface. The first is a camera attached to the base of the crane as to simulate the view from the "cockpit" of the crane. The second is mounted as an overview of the entire crane workspace. This camera allows users a complete view of the crane at any time.

3. CRANE-BASED CURRICULUM

Since 2001, Georgia Tech has been developing a crane-based curriculum to improve system dynamics and controls courses. Both the large and small-scale cranes have been used by students to conduct experiments. These learning tools supplement homework and lecture material with interactive and real-world examples of system dynamics, vibrations, and control techniques.

3.1 Homework Problems

A series of homework problems progressively increases the students' understanding of crane dynamics and control. These problems introduce students to MATLAB's simulation and plotting capabilities, teach students how to combine mechanical and electrical subsystems, and demonstrate how input shaping reduces vibration [Forest et al., 2001].

The first problem requires the students to derive the dynamic model of a planar gantry crane. Students then use

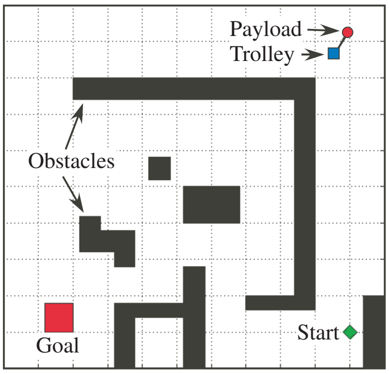


Fig. 10. Bridge Crane Simulation

MATLAB to plot the response of the crane to several inputs - step, pulse, and bang-bang functions. In the second homework assignment, the students add a motor to the planar gantry crane from the previous problem. The result is that the motor dynamics delay the crane response. In the third homework problem, students thoroughly analyze the response of the original planar crane model to a bang-bang function and an input-shaped bang-bang function. Most recognize that the vibration is cancelled in some way for the input-shaped command. Classroom instruction explains input-shaping, showing the students how inputs to the system, timed appropriately according to the systems natural frequency and damping ratio, can cancel vibration.

3.2 Bridge Crane Simulation

After the preliminary homework assignments, the students are given a MATLAB simulation of a gantry crane operating in a cluttered workspace. The operator's viewpoint is directly above the workspace, shown in Fig. 10. The workspace contains a starting zone, goal location, obstacles, and the crane trolley and payload. The crane's trolley is controlled by using the numeric keypad on a computer's keyboard.

The objective is to move from the starting zone to the goal location in the fastest and safest way possible. Each student is given a score based on their crane-driving performance. The score consists of the time-to-completion plus time penalties that are added for collisions. Although scoring does not influence grades, giving the students a score ensures some level of effort from the students. Each student drives the crane with and without input shaping. This allows the students to see the benefits of a vibration control scheme like input shaping. Even the relatively simple simulation proves a strong positive reinforcement of the material that students learn in lecture.

3.3 10-Ton Industrial Bridge Crane Labs

The primary use of the 10-ton industrial bridge crane at the undergraduate level has been as a demonstration of crane dynamics and advanced controls techniques, such as input shaping. Students are able to operate the crane and gain first-hand experience in the difficultly in accurately positioning crane payloads. Students also operate the crane with input shaping enabled, demonstrating the effectiveness of this control technique. At the graduate level, the industrial bridge crane has been used for numerous term projects. Teams of graduate students have implemented their own controllers and conducted numerous experimental investigations. For example, sixty students from an aerospace engineering dynamics course were recently able to operate the crane as part of their coursework.

Despite its effectiveness, the 10-ton Industrial Bridge Crane has one main disadvantage as an educational tool. The crane is in active use at Georgia Tech. This makes it challenging to schedule lab time for the students and limits the modifications to the control architecture that the students can safely make. This fact motivated the design and construction of the smaller-scale, portable cranes discussed in Sections 2.2–2.4 and the development of the lab sequence discussed in the next section.

3.4 Portable Crane Labs

The laboratory sequence discussed in this section can be applied to any of the portable cranes discussed previously. The progression also easily scales to varying difficulty levels, making it suitable for both undergraduate and graduate courses. The labs are divided into three main subdivisions: introductory labs, oscillation control labs, and final group projects.

Introductory Labs The introductory labs serve to introduce the students to dynamic properties of the portable cranes, as well as the operating and programming procedures. The first introductory lab uses simple programming of the PLC to observe the response of the crane to various commands. Students observe the compromise between rapid motion and payload oscillation.

During the second introductory lab session, more advanced programming is required and students begin to apply the control design techniques that they have learned in lecture. For example, students are asked to tune PI controller gains to achieve small trajectory tracking error of the trolley and small payload oscillation. Students quickly realize that increasing the PI gains will improve tracking error. However, students also realize that choosing lower PI gains reduces payload oscillation because it causes a sluggish trolley response. The exercise reinforces one of the fundamental compromises in control design for flexible systems.

A third introductory lab focuses on the dynamics of the portable cranes. Students are asked to vary operating parameters, such as suspension cable length, and observe the effect on the response of the crane payload. The effects of the parameter variations are compared to theoretical predictions that the students develop, and the effect on their previously developed controllers is examined. This exercise demonstrates the necessity for robust control methods.

Oscillation Control Labs These labs focus on reducing payload oscillation. Portions of these labs are well suited to graduate level courses as they provide practical experience with the implementation of advanced theoretical concepts. Students are required to implement one or more advanced controls technique, such as model reference control [Landau, 1993] or zero phase error tracking control (ZPETC) [Tomizuka, 1987]. The effectiveness of these controllers is compared to the simpler methods used in earlier labs.

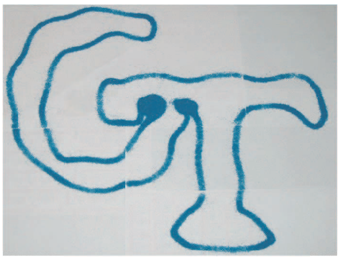


Fig. 11. Student Project: Using Sand to Spell out "GT"

Given the success of input shaping as a crane control method [Starr, 1985, Singer et al., 1997, Parker et al., 1999, Khalid et al., 2006, Sorensen et al., 2007b, Singhose et al., 2007], a large portion of this section of the lab progression is devoted to it. Students are lead through input-shaping techniques over a series of three to five laboratory sessions. This progression begins with the design and implementation of an input shaper designed for a single suspension cable length. The students compare the system response to commands generated using the shaper to the unshaped responses they measured during the introductory lab exercises.

In subsequent labs, students examine the robustness of various input shapers to changes in system parameters. During the examination of the input shaper robustness, students are exposed to one fundamental compromise in input shaper design; increasing shaper robustness increases shaper duration and, as a result, system rise time. Students are also asked to design and implement an input shaper to cancel two modes of vibration, which occur for certain crane payload configurations [Singhose et al., 2007, Vaughan et al., 2007].

Tracking control is another subject covered during this oscillation control portion of the lab progression. The students are assigned the task of navigating through an obstacle field with two different payloads, one of which results in double-pendulum effects. The students must use a single controller for both payloads. Students are not explicitly required to use input shaping, but many do. This lab further reinforces the necessity of robust control design techniques and helps push students toward the integration of the various control techniques covered in the course. This lab has also been conducted under the framework of a design competition, where the team with the fastest times is named the winner.

Final Projects In an effort to further push students toward internalization of control techniques, the students are required to complete a five-week final project. The students are required to design and conduct novel control experiments. This forces the students to use concepts outside of the bounds of what is taught in class. They must not only understand the ideas, but synthesize new ones. For example, one group used the crane to dispense sand and write "GT", as shown in Fig. 11.

The implementation of a final project has been a particularly successful endeavor. Three of the final projects from the fall 2005 session of a graduate level controls course were presented at international conferences [Huey et al., 2006, Blackburn et al., 2006, Bradley et al., 2006]. Class projects from the fall of 2006 section of the course also resulted in quality, published research [Sorensen et al., 2007a, Enes et al., 2007].

4. INTERNATIONAL COOPERATION

During the fall of 2005, two parallel, graduate level courses were taught at Georgia Tech and Tokyo Tech (Tokodai). The Georgia Tech students primarily used the bridge crane in Atlanta. The Tokyo Tech students primarily used the tower crane, which was shipped to Tokyo for use in the course. The Japanese course taught command generation and feedforward control, with an emphasis on real-world complications. The students used the crane in three ways: to perform labs, to conduct and participate in a remote manipulation study, and to collect data for their final projects. Because the two courses were taught in parallel, the U.S. and Japanese students had the opportunity to collaborate on their final projects.

The students were given the option of choosing one of three projects:

(1) Consider a crane where the trolley accelerates up to speed faster (or slower) than it can brake. Test a new input shaper developed for this nonlinear effect [Lawrence et al., 2006b] and develop an improved version of the shaper if possible.
(2) Both tower and bridge cranes are governed by nonlinear dynamics. Given the equations of motion, verify these nonlinear dynamics and develop controllers that compensate for these nonlinearities.
(3) Study remote operation of tower and bridge cranes. Perform studies that test the effectiveness of input shaping when used to remotely control cranes.

Because the final projects were performed near the end of the course, the students were well trained on how to use both cranes and collect data. In addition, since both cranes could be controlled remotely, the students in Japan or the U.S. could use either crane.

Due to the timing of the U.S. and Japan classes, the U.S. teams completed their final projects first. Then, the Japanese students were given the same projects along with the results from the U.S. students. Their task was to further develop the projects and improve the results from the U.S. students. In the final stage, the Japanese groups and their U.S. counterparts came together to write conference papers on their work [Blackburn et al., 2006, Bradley et al., 2006, Huey et al., 2006].

In addition to the Tokyo Tech collaboration, the portable cranes have been operated by researchers and students located throughout the United States, Japan, Korea, Switzerland, Spain, and Serbia.

5. USE OF CRANES FOR UNDERGRADUATE RESEARCH

The cranes also provide an excellent opportunity for undergraduates to get involved in research. In fact, numerous undergraduates have already used the cranes to conduct research that has resulted in technical publications [Lawrence et al., 2006a,b, Khalid et al., 2006, Huey et al., 2006, Bradley et al., 2006, Kim and Singhose, 2007a,b, Singhose et al., 2007, Suter et al., 2007, Vaughan et al., 2007, 2008a,b].

6. CONCLUSIONS

Cranes provide an excellent platform for system dynamics and controls education. Their pendulum-like oscillations are easily observable and make precise payload positioning difficult. The ability to address additional dynamic effects makes cranes an easily scalable educational tool. This paper reviewed the use of cranes in system dynamics and controls courses at Georgia Tech. It presented the capabilities of the four cranes and a crane-based curriculum developed to utilize them. International collaborations utilizing the cranes were also presented.

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