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A Small-Scale Cherrypicker for Experimental and Educational Use

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***Abstract*— Cherrypickers are a useful class of machines that lift people to great heights. However, a major drawback of cherrypickers is that they oscillate when they move. Understanding the dynamics and stability of these machines is crucial for efficient and safe operation. To this end, a small-scale cherrypicker was constructed for experimental dynamic analysis and educational use. Experimental results confirm the benefits of the vibration-control techniques developed for this machine. The cherrypicker was used during Fall 2010 as an experimental apparatus in an advanced graduate controls course taught simultaneously at the Georgia Institute of Technology and the Massachusetts Institute of Technology. Details of its educational use are discussed.**

I. Introduction

Aerial lifts raise people high up so that they can work on power lines, buildings, airplanes, and similar elevated structures [1]–[3]. Figure 1 shows an aerial lift that uses a scissor mechanism to extend straight upwards. Figure 2 shows a different type of aerial lift, often called a cherrypicker. This type of lift uses a jointed arm to extend not only upward, but also out from the truck that forms its base.

The cherrypicker has a much larger workspace than the scissor lift. However, given that it can extend out from the base, it will oscillate, and can even tip over. Oscillations of the workers can cause work delays, injuries, and property damage. Examples include when the bucket oscillates into a glass-sided building and when the bouncing bucket touches power lines. If the machine tips over, then the result can be catastrophic. For example, the cherrypicker shown in Figure 2 tipped over at the Miami airport when workers where installing an antenna on the tail of a DC-8 airplane. One of the workers died and the other was severely injured.

Various types of control methods can be used to improve the dynamic response of cherrypickers. One command-shaping technique that can be used to reduce the oscillation induced by system motion is input shaping [4]–[6]. The input-shaping process is demonstrated in Figure 3. The original step command, shown at the top of the figure, induces an oscillatory response. If it is convolved with impulses, called the input shaper, then the shaped staircase command will be created. This shaped command can then move the system without inducing large oscillations, as shown on the bottom of Figure 3.

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Figure 1. Scissor Lift

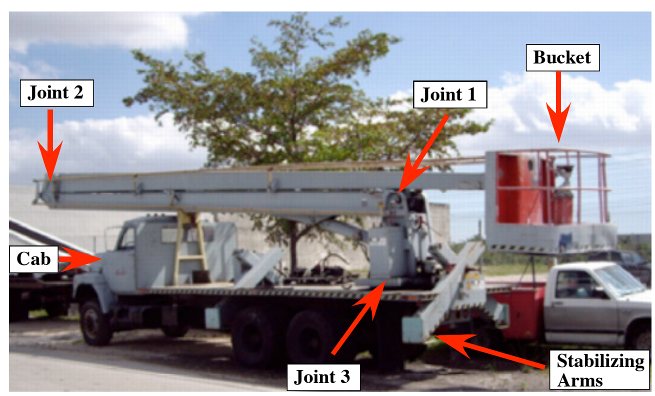

Figure 2. Cherrypicker Involved in Fatal Accident at Miami Airport

A small-scale cherrypicker has been constructed for use as an experimental and educational testbed. The cherrypicker is shown in Figure 4. The machine corresponds closely with a robotic arm that has a slewing base and a two-link jointed arm [7]–[11].

During the Fall 2010 semester, an advanced controls course at the Massachusetts Institute of Technology utilized the machine in several laboratory exercises. The MIT students used the machine to study the vibration problem inherent to cherrypickers, as well as evaluate the various control systems they developed to improve the performance.

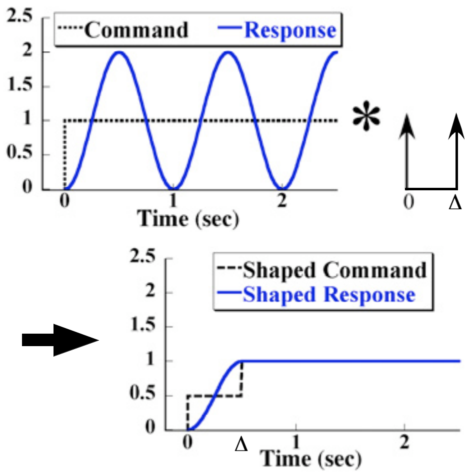

Figure 3. Input-Shaping Process

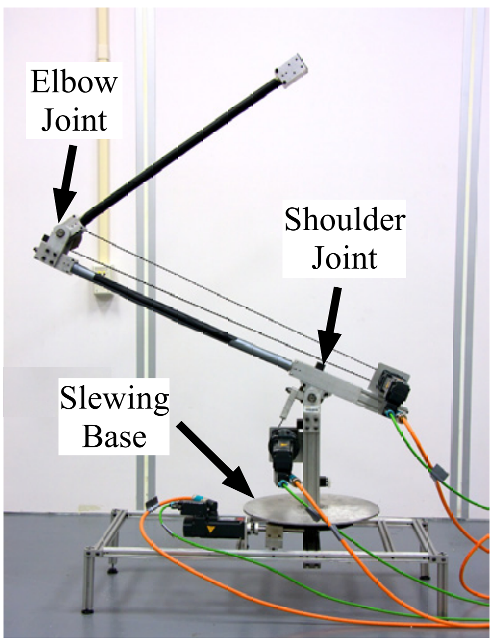

Figure 4. Small-Scale Cherrypicker

Concurrently, students at the Georgia Institute of Technology used other small-scale flexible machines to conduct similar experiments [12], [13]. The MIT and Georgia Tech students collaborated to conduct meaningful research for their course projects. Several of the MIT students traveled to Georgia Tech at the end of the term to help present their group projects to a panel of industrial and academic judges.

This paper presents the experimental and educational usage of the small-scale cherrypicker to date. Section II describes details of the mechanical design. Section III presents sample experimental results that illustrate the dynamics and control of the cherrypicker. Finally, Section IV presents a discussion of its use as an educational tool.

II. Mechanical Design

The cherrypicker shown in Figure 4 is equipped with three Siemens synchronous servomotors that drive the slewing base, shoulder joint, and elbow joint. The motors are controlled via Siemens SINAMICS motor drives with Proportional-Integral feedback control on the reference velocity. The cherrypicker is controlled by a Programmable Logic Controller (PLC) that is connected to a laptop computer via an ethernet connection. Each motor is equipped with an encoder that outputs velocity and absolute position. The endpoint of the cherrypicker is tracked by a machine vision system placed to the side of the machine.

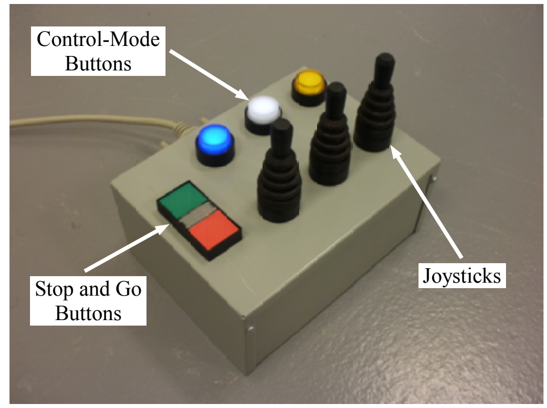

Figure 5. Control Box

The cherrypicker can be operated via the control box shown in Figure 5 or a Graphical User Interface (GUI). The stop/go buttons on the control box change the machine state between inactive and active. The three joysticks control the three axes of motion. The round buttons enable the various control modes of the machine.

The cherrypicker can be remotely operated via the GUI through a Virtual Network Computing (VNC) connection. The left side of the GUI is shown in Figure 6. The top area contains buttons that control each axis of motion. When the operator moves the cursor over one of the six directional arrows and presses the mouse button, a constant velocity command is send to the PLC and the motor drives. When the operator releases the mouse button, the motion comes to a stop. The bottom area provides several control options. The type of input shaper can be selected, a pre-planned trajectory can be uploaded and executed, velocity and position data can be recorded and downloaded, and the control inputs can be changed to a different coordinate system. The right side of the GUI is shown in Figure 7. This portion of the GUI presents the real-time position of the cherrypicker from top and side views. In Figure 7, the shoulder joint angle (i.e. the angle of the lower link relative to the horizontal) is 25° and the elbow joint angle (i.e. the angle of the upper link relative to the lower link) is 24°. The joint angles and the dynamic sketches provide tele-operators with the current configuration of the cherrypicker.

III. Experimental Results

The natural frequency and damping ratio of the cherrypicker were experimentally determined while the cherrypicker arm was in the extended position (both shoulder and elbow joint angles equal zero). The frequency was approximately

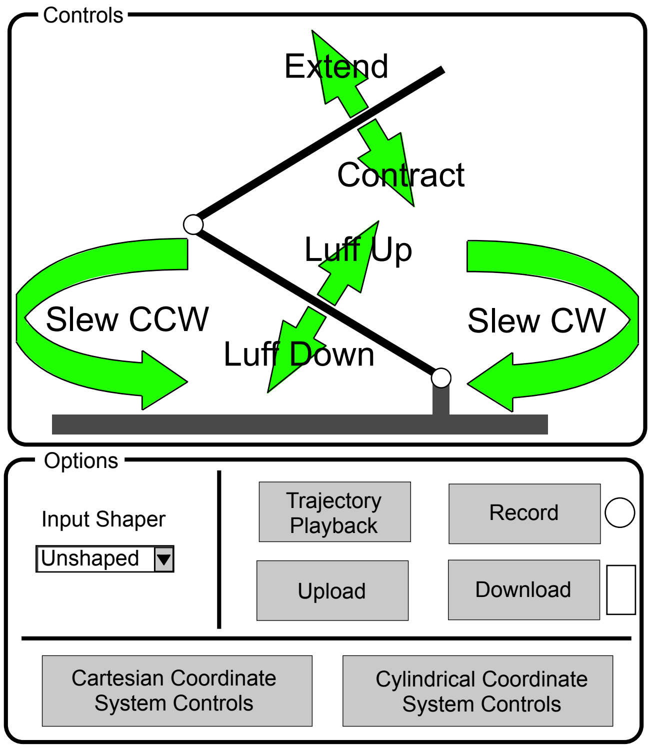

Figure 6. Left Side of GUI

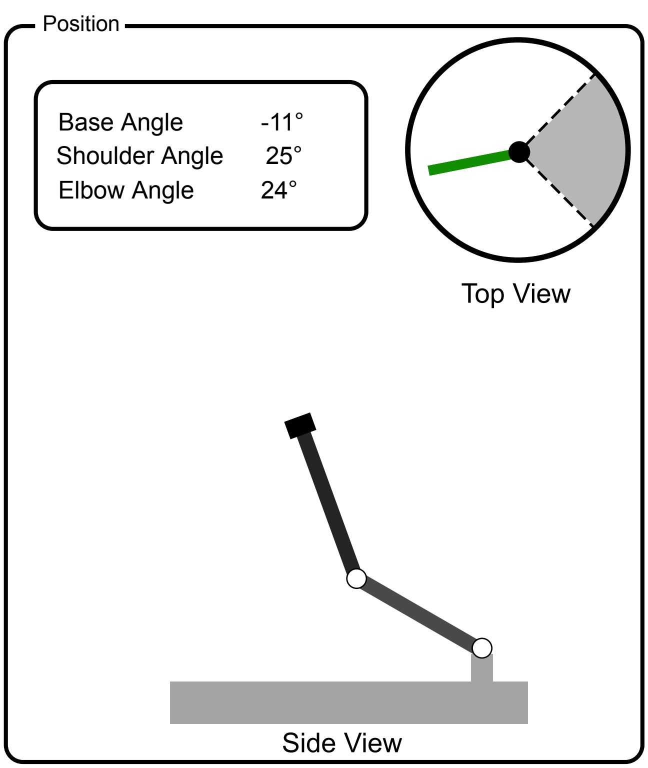

Figure 7. Right Side of GUI

2 Hz, and the damping ratio was approximately 0.08 using the log decrement method.

Figure 8 shows the position of the tip of the arm for a 10° shoulder rotation. The elbow joint angle was fixed at 0°. The endpoint position was recorded by a camera placed to the side of the cherrypicker. The figure focuses on the residual oscillation of the arm endpoint (the transient oscillation during the move is not shown). This figure demonstrates the vibration problem associated with cherrypickers. The endpoint undergoes large oscillations before settling at its final position.

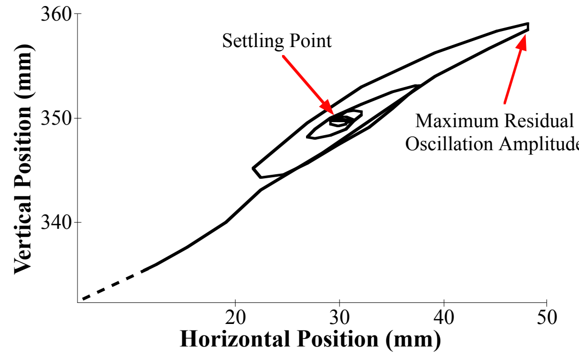

Figure 8. Endpoint Vibration for 10° Shoulder Joint Motion

TABLE I. Input-Shaper Parameters

ZV	t_i	0	0.200	
	A_i	0.56	0.44	
SI	t_i	0	0.261	0.519
	A_i	0.33	0.46	0.21

In order to control the oscillation of the cherrypicker arm, two different input shapers were designed. The Zero Vibration (ZV) shaper [4], [5] was designed using the empirically-determined parameters in the extended configuration ($f = 2$ Hz, $\zeta = 0.08$). The Specified Insensitivity (SI) shaper [14] was designed to suppress oscillation frequencies between 1.5 Hz and 2 Hz. The suppression level was set to 5% of the unshaped oscillation amplitude. This frequency range was selected because when the endpoint mass increases (e.g. people and tools are loaded into an empty bucket at the tip of the arm), the natural frequency decreases. The impulse amplitudes (A_i) and times (t_i) of these two shapers are given in Table I.

As was shown in Figure 8, the first experiments rotated the shoulder joint, while holding the elbow angle at zero (fully extended). The arm endpoint position for a 15° shoulder joint motion is shown in Figure 9. The horizontal positions of the responses with the ZV and SI input shapers have been shifted to the right for clarity. The unshaped move caused a residual vibration amplitude of 33 mm. The ZV- and SI-shaped commands reduced the residual oscillation to only 10 and 12 mm, respectively.

Longer shoulder joint rotations of 30° and 45° were also tested. The results are summarized in Table II. Unshaped commands induced vastly different amounts of residual oscillation for different move distances. This variation occurs because the oscillations induced by the acceleration and deceleration are sometimes in-phase, so they add to increase

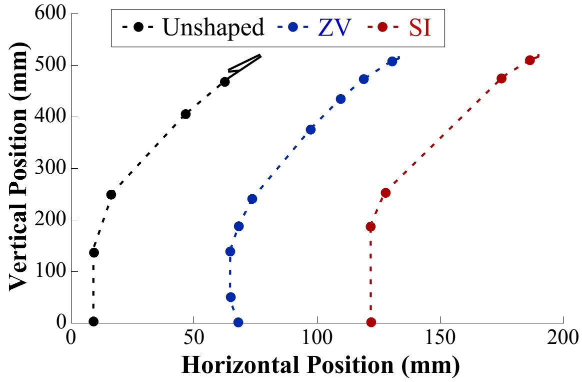

Figure 9. Endpoint Position for 15° Shoulder Joint Motion, Unweighted Endpoint

TABLE II. Endpoint Oscillation Induced by Shoulder Joint Motion

Command	Unweighted (mm)			Weighted (mm)		
	15°	30°	45°	15°	30°	45°
Unshaped	33	41	58	132	103	108
ZV	10	12	27	106	47	92
SI	12	21	23	22	15	26

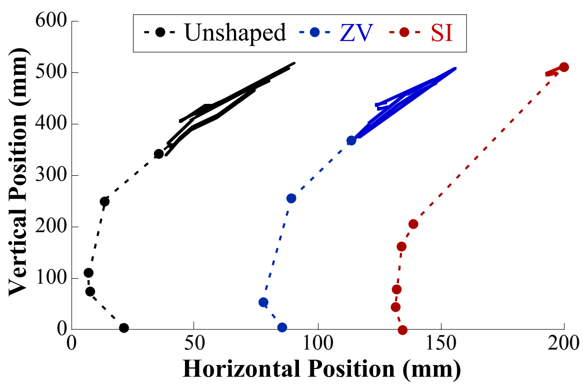

Figure 10. Endpoint Position for 15° Shoulder Joint Motion, Weighted Endpoint

the residual vibration. In other cases they are out-of-phase, so the vibrations partially cancel each other out. The ZV- and SI-shaped commands consistently reduced the vibration relative to the unshaped command. The ZV- and SI-shaped commands reduced the residual oscillation by an average of 63% and 58% over the three distances tested, respectively.

To study changes in the cherrypicker dynamics when the payload mass increases, the mass at the tip of the arm was increased by 50%. This lowered the natural frequency by approximately 20%. The endpoint position of the arm for the 15° shoulder joint rotation is shown in Figure 10. The unshaped command induced larger residual vibration than for the unweighted case shown in Figure 9. The ZV-shaped command also induced large residual oscillations because the shaper is not robust to variations in the frequency. However, the robust SI shaper was able to significantly reduce the residual oscillations. The ZV- and SI-shaped commands reduced the residual oscillation by an average of 29% and 82% over the three distances tested, as shown in Table II.

TABLE III. Endpoint Oscillation Induced by Elbow Joint Motion

Command	Unweighted (mm)			Weighted (mm)		
	36°	48°	60°	36°	48°	60°
Unshaped	15	50	23	51	47	18
ZV	11	10	11	26	15	13
SI	12	10	10	16	10	10

During a second set of experiments, the elbow joint was moved while the shoulder joint was fixed at 0°. Move distances of 36°, 48°, and 60° were tested using unshaped, ZV-shaped, and SI-shaped commands. For these motions, the natural frequency of oscillation increased relative to the frequency that occurred in the first set of tests. The residual oscillation amplitudes from both unweighted and weighted cases are given in Table III. The residual vibrations induced by the unshaped commands were relatively large and varied across different move distances. Both the ZV- and SI-shaped commands suppressed the residual oscillation by an average of 64% in the unweighted case. The robust SI shaper again performed better than the ZV shaper when payload mass was increased. The ZV- and SI-shaped commands suppressed the residual oscillation by an average of 53% and 69% in the weighted case, respectively.

These results confirm the effectiveness of input shaping on this nonlinear machine. The ZV shaper suppressed the residual oscillation well for both joint motions as long as the actual frequency did not vary greatly from the modeled frequency. However, to accommodate substantial payload increases (which decrease the system frequency) a more robust SI shaper was required to reduce the residual oscillation across both unweighted and weighted tests, and for both axes of motion.

IV. Educational Results

The cherrypicker was used at MIT in an advanced controls course entitled "Command Shaping: Theory and Applications." This course corresponded to a similar course taught simultaneously at Georgia Tech entitled "Advanced Control Design and Implementation." The students at Georgia Tech utilized other small-scale machines, such as a tower crane [12], [15] and bridge crane [13], [16].

The first laboratory assignment required the students to move the cherrypicker arm at various velocities. One of the main goals of this lab was to provide the students with a general understanding of how to operate the machine and gather data. In addition, the students observed and measured the oscillation that is inherent to cherrypickers.

The second laboratory investigated control of suspended payloads. As shown in Figure 11, a payload was attached to the tip of the arm via a suspension cable. The students tuned a Proportional-Integral (PI) feedback controller on the shoulder and elbow joints. They optimized the P and I gains using trial-and-error. They attempted to optimize the gains for two competing objectives: 1) force the motors to closely follow

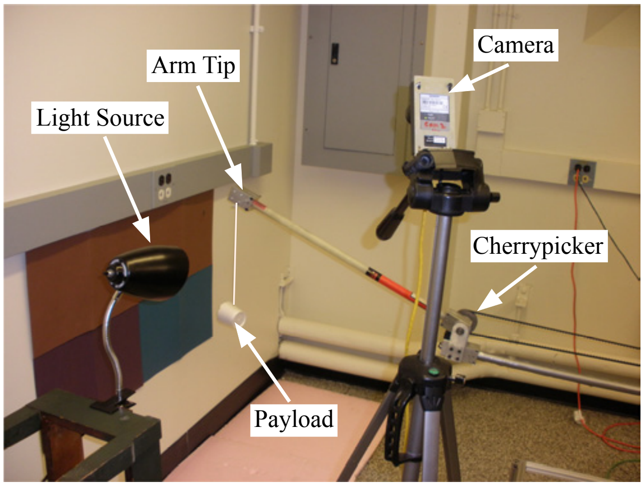

Figure 11. Suspended Payload Set-up

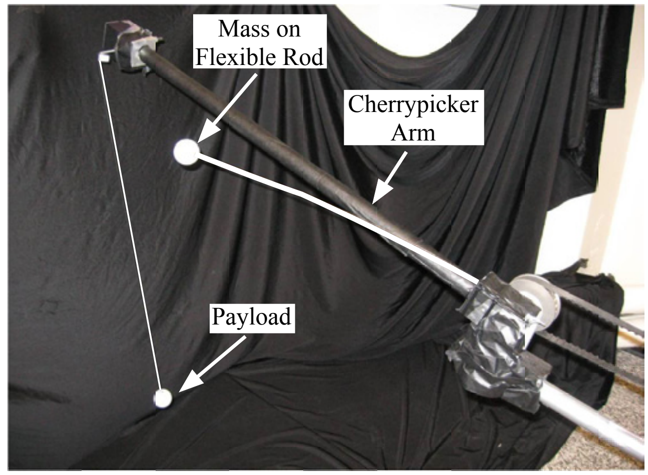

Figure 12. Lab 4 Set-up

a pre-designated velocity profile and 2) produce minimal residual oscillation. To track a trajectory, the gains need to be relatively high to allow the motors to rapidly change speed and follow the desired trapezoidal velocity profile. However, to decrease the residual oscillation of the suspended (and unmeasured) payload, the gains must be small.

The third lab exercise required the students to design an input-shaping controller. They developed various input shapers and compared their effectiveness for different move distances and suspension cable lengths, thereby determining their robustness to parameter variations. Next, the students were asked to experimentally determine the frequency of the arm oscillation in the extended position. Then, they used that information and the empirically-determined frequency of the suspended payload swing to design a two-mode input shaper [15], [17], [18] and test its robustness.

In the fourth lab exercise, the students analyzed Specified Negative Amplitude (SNA) input shapers [19]. SNA shapers are faster than their positive counterparts. However, because they generate more aggressive commands, they have a tendency to excite higher unmodeled modes of the system. The cherrypicker was equipped with a point mass attached to a flexible rod at the tip of its arm. Figure 12 shows this set-up. The mass on the flexible rod served as the unmodeled higher mode. SNA shapers were designed for the frequency of the pendulum swing and their effect on the oscillation of the flexible rod was analyzed.

During the last six weeks of the course, the students at MIT and the students at Georgia Tech collaborated on term projects. Some of the projects performed were: Wind-Induced Disturbance Rejection on a Bridge Crane, Intelligent Use of A Priori System and Trajectory Knowledge, and Human Interface and Controller for Positioning a Model-Scale, Radio-Controlled Helicopter with a Sling Load. The success of the projects was judged by a panel of judges from industry and academia. Some of the MIT students traveled to Georgia Tech to help present their team's projects to the judges.

V. Conclusions

A small-scale cherrypicker was constructed for experimental and educational use. The cherrypicker was designed to provide a robust testbed for a variety of experiments. The control interfaces provide simple means for both local and remote operation. Experimental results demonstrated that a Specified Insensitivity input shaper can greatly reduce the residual endpoint vibration, even in the presence of frequency changes. The cherrypicker was used in an advanced controls course at MIT during the Fall of 2010. The students performed various experiments on the machine, including designing and implementing their own control algorithms.

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