DOUBLE-PENDULUM CRANE OPERATOR PERFORMANCE COMPARING PD-FEEDBACK CONTROL AND INPUT SHAPING

Ajeya Karajigikar †, Joshua Vaughan † and William Singhose †

†Woodruff School of Mechanical Engineering
Georgia Institute of Technology,
Atlanta, GA 30332

e-mail: ajeya@gatech.edu, vaughanje@gatech.edu, Singhose@gatech.edu

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Abstract. A primary limitation on crane operations is the difficulty of controlling payload oscillations. Given the significance of cranes, it is not surprising that a large amount of research has been dedicated to eliminating crane payload oscillation. Numerous feedback-based control methods have been proposed. Command-shaping is another method that has received significant attention. This paper compares the two methods for double-pendulum crane control. Using feedback control on double-pendulum cranes can be quite challenging because sensing the payload and hook motion is difficult. The paper presents a study of ten novice crane operators using representative two-mode input shaping and feedback-control methods. In this study, both feedback control and input shaping reduced average task completion time from the manually controlled case; however, input shaping provided the lowest average completion time. Input shaping also allowed the operators to move the trolley over a shorter total path length to complete the tasks, suggesting that input shaping may save energy compared to feedback and manual control methods. Implementing input shaping also resulted in zero obstacle collisions during the tests thereby improving safety.
1 INTRODUCTION

Cranes have a wide range of applications in manufacturing, construction, and shipping port activities. Thus, improving crane efficiency and safety can have a great impact on a wide variety of industries. All cranes share the same problem of inefficiency caused by payload oscillations. Payload swing makes it difficult to manipulate payloads quickly, accurately and safely. The problem is further compounded when the payload creates a double-pendulum effect. This paper compares the control of a double-pendulum crane payload with input shaping and PD-feedback control. The results of crane operator studies comparing these two control methods are also presented.

To illustrate this problem, consider the double-pendulum crane model in Fig. 1. In this planar model, the hook is connected to the crane trolley via an inflexible cable of length $l_1$ and the payload is attached to the hook with a massless, inflexible rigging of length $l_2$. The mass of the hook and payload are $m_h$ and $m_p$, respectively.

Example trolley and payload responses for a simple, point-to-point move are shown in Fig. 2. The payload oscillates around the trolley position during and after the move. This oscillation makes it difficult to accurately position the payload and increases task completion time, while decreasing safety. The frequencies and the associated amplitudes depend heavily on the payload configuration [1–4].

Many researchers have suggested feedback methods to control payload oscillation. A thorough review of these techniques developed during the 20th century is presented in [5]. However, to achieve reliable feedback control, critical challenges in crane operation must be overcome. The first problem is that most researchers assume that the crane payload is well known and its states are easily sensed. This is typically not the case. Crane payloads continually change, leading to varying dynamic effects, especially when the crane payload and hook create double-pendulum effects. These changing dynamics are especially difficult for feedback control systems; unknown and/or greatly varying high-modes are difficult to control and can lead to instability.

In addition to the lack of knowledge about payload characteristics, payload states are also very difficult to sense. Several payload sensing systems have been proposed, but they are either impractical in real working conditions or very expensive, which limits their use to a small fraction of expensive cranes.
Another major factor of crane operation that should be considered during control design and implementation is the fact that nearly all cranes are controlled by human operators. This has several important implications. The first of these is that the crane control system needs to be compatible with human operators. Systems that create non-intuitive crane behavior can be unsettling to the crane operator and, as a result, ultimately detrimental to crane performance. The second factor is that the human operator is a feedback controller. It is well known that competing feedback controllers can degrade performance. This is especially true given that the human feedback control properties can vary widely from task-to-task and from operator-to-operator. The changing human feedback control properties can make it difficult to tune computerized feedback control systems for compatibility.

Input shaping is a control method that reduces payload oscillation by filtering the human-operator commands \[6, 7\]. This approach has several advantages over feedback-based controllers. One main advantage is that no computerized feedback is used, leaving the human operator as the sole feedback controller. As such, it is compatible with human operators, as supported by the results from numerous crane-operator studies \[3, 4, 8, 9\].

All that is needed to implement input shaping are estimates of the natural frequencies and damping ratios (which are near zero for most cranes). A major advantage compared to feedback control is that, for input shaping design, these estimates need not be calculated in real time. The input shaper can also be made robust to changes in these frequencies and damping ratios with little penalty \[7, 10, 11\].

In the next section, the challenges of using feedback for crane control are discussed in detail. Then, in Section 3, the input-shaping method is reviewed. The advantages and disadvantages of each method are discussed throughout the text. The implementation of a PD-feedback controller and an input-shaping controller on a 10-ton industrial bridge crane is discussed in Section 4. A study of ten novice crane operators is then presented in Section 5.

2 USING FEEDBACK CONTROL ON CRANES

One major challenge of implementing feedback control systems on crane is the difficulty in accurately and robustly sensing the crane payload. Another major challenge is human-operator compatibility. This section will discuss these two challenges in more detail.

2.1 Sensing Crane Payloads

In order to successfully implement a feedback control system, there must be some way to accurately and reliably sense the system motion. Many researchers proposing feedback methods for crane control assume that either the payload or hook can be easily sensed. In practice, this assumption proves false.

However, there are a few methods that have been used with some success: machine vision, gyroscopes and simple, angle sensors are examples. Some researchers have proposed vision systems mounted throughout the crane workspace and have shown them to work well in laboratory conditions \[12, 13\]. Cranes at Georgia Tech \[14\] and Logan Aluminum \[15\] have been equipped with trolley-mounted vision systems to track the crane hook. However, machine vision has several potential drawbacks. The systems mentioned above were all located in fairly
controlled environments, where lighting conditions were fairly constant and background clutter was minimal. Many cranes operate in conditions that are significantly less ideal. Vision systems will have additional difficulties in the crowded, harsh, and changing environments in which many cranes operate. For example, a vision system on a tower crane like the one shown in Fig. 3 would have to be able to separate the hook and payload from the background clutter of the surrounding buildings and streets. It would also have to do this over a very large range of suspension cable lengths.

Even under ideal conditions, sensing the crane payload is not trivial. One obvious location to mount a machine vision system is overhead, attached to the crane trolley. This provides the best opportunity to keep the crane hook and payload in the camera field-of-view. In this configuration, tracking the crane hook is the most straightforward, given the correct environmental conditions (lighting, etc.). However, the crane hook and suspension cables obscure the camera’s view of the payload. For example, the image in Fig. 4 was taken by a trolley-mounted camera. The hook and suspension cables fill a significant portion of the image, blocking the payload below.

Other researchers have used gyroscope-based sensing solutions with some success [16–18]. In this work, the gyrosopic measurements are often coupled with secondary means of sensing, such as potentiometers measuring cable deflection, and observers are used to smooth the resulting signals. The design and implementation of such observers introduces an additional layer of complexity to the system.

In addition to the difficulties associated with sensing the location of the payload, most crane feedback controllers also require accurate knowledge of higher-order states, such as the velocity of the payload. With constantly varying payload sizes, shapes, material, etc., measuring higher-order states can be much more challenging than sensing payload location. With each additional sensor necessary to measure the states of the payload, additional complexity, design
time, failure modes, and cost is added to the controller.

2.2 Conflict Between Feedback and Human Operators

Another major challenge of implementing feedback control is conflict with human operators. For pre-designated motions, feedback control of cranes, ignoring the difficulties mentioned above, can work well. However, most cranes are not operated via a computer or driven through pre-defined trajectories. Rather, they are controlled in real time by human operators. Herein lies the challenge. The human operator provides not only the initial reference command to the crane, but also introduce adjustments and additional feedback as necessary to maneuver the crane through the desired trajectory. Any additional input from a computerized feedback controller can adversely conflict with the input from the human operator. For example, crane operators at the Port of Savannah in Georgia intentionally disable the anti-sway feedback systems because they interfere with their "expert" methods of manually eliminating swing.

3 INPUT SHAPING

Input shaping is a command shaping method that has been successfully used to limit crane payload oscillations \[2-4, 8, 9, 19\]. Another related method uses Infinite Impulse Response (IIR) filters \[20\]. Figure 5 demonstrates the input-shaping process. A series of impulses is convolved in real-time with the original reference command to create a shaped command. In Fig. 5 the original velocity pulse command is transformed into a staircase command that moves the system without oscillation.

The amplitudes and time locations of the impulses that compose an input shaper are designed using estimates of the natural frequencies and damping ratios. There are always errors in these estimates, so input shapers can be made robust to changes in these parameters \[7, 10, 11\]. This is a much different requirement than knowing the states of the system in real-time, as is needed with feedback control. To design an input shaper, these estimates can be determined, and the design can be completed offline. Once the shaper is designed, no further knowledge of the crane states is needed. In addition, shapers can be designed to account for system nonlinearities \[21, 22\] and to eliminate multiple modes of vibration \[2, 23-25\].

In addition to eliminating the need for payload sensors, the command-shaping nature of the control system is compatible with human operators. This fact is supported by numerous studies of crane operators \[3, 4, 8, 9\]. The primary disadvantage of input shaping is that it is unable to reduce oscillation caused by disturbances to the hook or payload, due to its open-loop nature.

![Figure 5: The Input-Shaping Process](image_url)
4 CONTROL OF A 10-TON INDUSTRIAL BRIDGE CRANE

Both feedback and input-shaping control methods were implemented on the 10-ton industrial bridge crane in Fig. 6. It has a workspace that is 6 meters high, 5 meters wide, and 42 meters long. Signals generated by the human operator travel from the push-button control pendant to the hoist controls and bridge-and-trolley control box. A Siemens PLC performs the control algorithms. The crane is also equipped with a Siemens vision system to track the hook response. This vision system is also the primary sensor when the feedback control system is used on the crane.

The block diagram in Fig. 7 is a conceptual representation of the feedback system implemented on the bridge crane. The machine vision system is used to feed back the hook deflection, $\theta$, to a Proportional-Derivative (PD) feedback controller. The human operator acts as a feedback controller on position, issuing velocity commands based upon the current and desired positions of the crane, $y$ and $y_d$, respectively. The commands created by the human operator are combined with those from the PD-controller on payload oscillation and issued to the crane.

It should be noted that the operating conditions of the crane tested here are favorable for the machine-vision-based feedback system. The area below the crane is generally clear of obstacles and other items that could make distinguishing the hook from the image background difficult. In addition, the lighting in the crane workspace is fairly constant, further reducing the necessary complexity of the vision system. On many industrial cranes, such favorable
conditions would not exist.

A block diagram of the input-shaping control system is shown in Fig. 8. Because input shaping does not require feedback, the control system structure is much simpler. The human operator still acts to position the crane. However, his/her commands are modified by the input shaper before they are issued to the crane so that they do not excite significant oscillation.

### 4.1 Example Point-to-Point Moves

To compare the effectiveness of the proposed control methods, straight line 3 m point-to-point moves were conducted on the crane in Fig. 6. For these trials, a 22.7 kg (50 lb) payload was attached to the 50 kg (110 lb) crane hook via a 1.8 m rigging. The resulting frequencies from this double-pendulum payload configuration were 0.26 Hz and 1.61 Hz. The PD-control gains and two-mode ZV input shaper [25] parameters were selected for this system configuration.

A response from a 3 m point-to-point move of the 10-ton bridge crane using “manual” control (no feedback or input shaping) is shown in Fig. 9. The hook oscillates around the location of the trolley both during the move and after it is completed. The low damping of the crane means that this oscillation continues for a significant amount of time, unless stopped manually. A similar move using the PD-feedback control system is shown in Fig. 10. The feedback controller greatly reduces the hook oscillation. The two-mode ZV shaper is able to reduce payload oscillation to nearly zero for this move, as shown in Fig. 11. The input-shaped response also exhibits lower oscillation during the move than the PD-feedback control system. This can be seen in Fig. 12 which shows the hook deflection for the three control cases. Both the peak amplitude of transient vibration and the residual amplitude of oscillation are lower with input shaping than with PD control. Both controllers provide significant improvements over the manually controlled case.

### 4.2 Example Point-to-Point Moves – Controllers Designed for Single Mode

As previously mentioned, sensing crane payloads is difficult. One control design option is to design the controller to eliminate only the low, pendulum mode and ignore higher modes. For many applications, this is a valid control strategy, as this lower mode dominates the oscillatory response. This section will examine the effect of ignoring the second mode of oscillation on
the crane with parameters identical to those tested in Sec. 4.1.

A PD-feedback control system that was designed to control the movement of a single-pendulum payload was implemented on the double-pendulum payload configuration [26]. The response of the crane for a point-to-point move with this controller is shown in Fig. 13. A single-mode Zero Vibration (ZV) input shaper [7] was also designed for the low mode of the crane and used to move the payload of a crane. Figure 14 shows the implementation of this one-mode ZV input shaper on the double-pendulum crane. Using a single-mode ZV shaper resulted in less oscillation of the payload than both the unshaped and PD-feedback controller designed for a single-mode, as shown by the hook-deflection plots in Fig. 15. Figure 16 shows all of the hook angle deviations for the five different control methods described above. This provides a clear comparison between the responses when the double-pendulum mode is considered during design and when it is not. It is clearly advantageous to account for the secondary oscillatory mode.

4.3 Double-Pendulum Controller Robustness

In order to test the robustness of the PD-feedback controller and the two-mode ZV shaper to changes in payload configuration, different masses were attached, but gains and shaper parameters left were left unchanged. The payload was first changed from 22.7 kg (50 lb) to 11.35 kg (25 lb). The result of the point-to-point move under PD-feedback control is shown
in Fig. 17. The result of the point-to-point move is shown in Fig. 18. The ZV-shaped response exhibits much lower oscillation than the PD controlled response, indicating it is more robust to the change in payload than the feedback controller.

The same PD gains and two-mode ZV shaper were used to move the crane with a 34 kg (75 lb) payload over a 3 m point-to-point move. The response under PD-feedback control is shown in Fig. 19. The result of the point-to-point move using the two-mode ZV shaper is shown in Fig. 20. It can be seen that using the ZV shaper reduces the residual oscillations even if there is a change in the payload mass. However, the PD-feedback controller exhibits significantly more payload oscillation than at the configuration for which it was designed.

5 STUDIES OF HUMAN CRANE OPERATORS

The effects of input shaping on human crane operator performance have been well studied [3,4,8,9]. Fewer studies have been conducted with feedback control methods. This section will present a study that compares operator performance with “manual” control to that with feedback control and with input shaping.
Ten novice operators were asked to complete a series of tasks using the industrial bridge crane. The crane operators completed trials on the obstacle course shown in Fig. 21. The task assigned to the operators was to move the crane payload from the 0.25 m diameter start circle, through a set of obstacles, to the 0.5 m diameter target as quickly and safely as possible.

The crane suspension cable length was set to approximately 3.5 m, and a rigging of 1.8 m was used to attach a 22.7 kg (50 lb) payload. Operators did not raise or lower the crane payload during any trial. Each operator completed the task with three different control methods: manual control (no feedback or input shaping), two-mode Zero Vibration (ZV) input shaping [25], and PD-feedback control. Prior to beginning the study, every operator completed the course with each control method to familiarize themselves with the control of the crane. Following this practice session, the trials began with the task order randomized to help mitigate operator-learning effects.

For each trial, the task completion time was recorded. Task completion time was measured from when the operator first moved the crane until the payload settled within the end zone. In addition, the total distance traveled by the trolley during each trial was calculated. The total travel distance gives an approximation of energy use; longer travel distances use more energy.
5.2 Operator Study Results

An example trial with manual control is shown in Fig. 22. The trolley tracks a safe path through the obstacle course and is easily positioned over the target location. However, the hook undergoes significant oscillation, making final positioning difficult. For this trial, the operator required 238 s to position the payload within the target region.

The same operator’s attempt to complete the task with the PD-feedback control system is shown in Fig. 23. The hook exhibited much less oscillation than during the manual controlled case, making positioning within the target region much easier. The trial was completed in 60 s, representing a 75% reduction from this operator’s completion time with the manual controller.

An example trial with the input-shaping controller from the same operator is shown in Fig. 24. Like the PD controller, input shaping drastically reduced the hook oscillation from the manual control case. The operator again was quickly able to position the payload in the target region; the trial was completed in only 35 s.

The task completion times for all ten operators are shown in Fig. 25. The PD controller and input shaping allowed every operator to complete the task more quickly than the manual controller. The average task completion time for each controller is shown in Fig. 26. The error bars indicate one standard deviation above and below the mean. The average completion time with PD-control was 66% less than manual control (55 s vs. 161 s). Input shaping further reduced the average completion time to 38 s, representing a 31% reduction from PD control and a
76% reduction from manual control. In addition, the standard deviation with the input shaping controller was less than with PD control, indicating that the performance varied less between operators. A one-way analysis of variation (ANOVA) test verified that the differences in completion time between methods were statistically significant, $F(2, 27) = 24.91, \; p \ll 0.001$. A paired $t$-test indicated that differences in completion time between PD-control and input shaping were less statistically significant, $t(18) = 1.99, \; p = 0.06$.

The average total distance the trolley traveled using each control method is shown in Fig. 27. The average distance the trolley traversed under manual control was 9.52 m. This is approximately 3 m more than the nominal path through the obstacle course. With PD control, the average travel distance was reduced to 9.07 m, a 5% reduction from manual control and closer to the distance required for the nominal path. The average distance traveled using the input-shaping controller was slightly less, 7.88 m. The shorter total travel distance afforded by input shaping provides evidence that is is more energy efficient than either manual control or PD control. However, a one-way ANOV A indicated that the differences in travel distance observed between control methods were not statistically significant, $F(2, 27) = 1.61, \; p = 0.22$. However, the differences seen in travel distance suggest that energy use between methods should be a goal of future investigations.

The number of collisions that took place when each of the operators moved the crane from the starting point to the end point is shown in Fig. 28. Each collision was defined to be the toppling over of the obstacle when the payload hit it. The total number of collisions in the unshaped case was 18 whereas in the PD-feedback case was only 2. The ZV shaped case resulted in no collisions throughout the study. The mean and standard deviation of the three cases is given in Fig. 29. A one-way ANOVA confirmed that the differences in number of collisions observed between control methods were statistically significant, $F(2, 27) = 15.28, \; p \ll 0.001$.

6 CONCLUSIONS

This paper discussed the use of feedback controllers and input-shaping controllers on cranes. The difficulties of implementing feedback controllers on cranes were outlined, including difficulty sensing the payload and human operator compatibility problems. Implementation of a representative feedback controller and input shaper on a 10-ton industrial bridge crane was also presented. Both the feedback control system and input shaping reduced oscillation of this
crane. A study of ten, novice crane operators demonstrated that the reduction in oscillation allowed the operators to more quickly complete crane positioning tasks. Of the control methods tested, input shaping produced the lowest average task completion times and shortest average trolley travel distance, while being the safest in terms of collision avoidance.

REFERENCES


