

A Study of Crane Operator Performance Comparing PD-Control and Input Shaping

Joshua Vaughan, Ajeya Karajgikar, and William Singhose

Abstract—Cranes are the primary heavy lifters for a wide variety of industries. However, all cranes suffer from payload oscillation. Numerous feedback-based control methods have been proposed to reduce oscillation. Command-shaping is another method that has received significant attention. This paper compares the two methods for crane control. It also presents a study of twelve novice crane operators using representative input-shaping and feedback control methods. Both feedback control and input shaping reduced average task completion time from the manually controlled case, with input shaping providing the lowest average completion time. Input shaping also allowed the operators to move the trolley through a shorter total path length toward the target, suggesting that input shaping may save energy compared to the feedback and manual control methods.

I. INTRODUCTION

Cranes are a vital component of many manufacturing, construction, and shipping port activities. Therefore, improving crane efficiency can have great impact on a wide variety of applications. A major limiting factor in safe and efficient crane operations is payload swing. Payload oscillation makes it difficult to accurately position the payload and increases task completion time, while decreasing safety. In addition, certain payload configurations induce multi-mode, double-pendulum effects that make control even more difficult [1]–[4].

Many researchers have employed feedback methods to control payload oscillation. A thorough review of these techniques developed during the 20th century is presented in [5]. However, in papers proposing feedback control, critical factors in crane operation are typically neglected. The first problematic assumption is 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 varying high-modes are difficult to control and can lead to instability.

In addition to the uncertainty of 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. This makes the implementation of any type of feedback method difficult.

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Another major factor that should be considered during crane 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 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 properties can make it difficult to tune computerized auxiliary feedback control systems.

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 control. One main advantage is that the human operator is 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 oscillation natural frequencies and damping ratios. 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 errors in these estimated frequencies and damping ratios with little penalty [7], [10], [11].

In the next section, the challenges of using feedback for crane control are discussed. Then, in Section III, the input-shaping method for crane control is reviewed. The implementation of a PD-feedback controller and an input-shaping controller on a 10-ton industrial bridge crane is discussed in Section IV. A study of twelve, novice crane operators is then presented in Section V.

II. FEEDBACK CONTROL FOR CRANES

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

A. Sensing Crane Payloads

In order to successfully implement a feedback control system, there must be accurate and reliable sensors. Many researchers proposing feedback methods for crane control



Fig 1. A Tower Crane in Seattle, WA

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 cable-angle sensors are a few 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 need to be located in fairly controlled environments, where lighting conditions are fairly constant and background clutter is 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 the tower crane shown in Fig. 1 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 under continual lighting changes over a massive workspace and 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. However, the crane hook and suspension cables obscure the camera's view of the payload. For example, the image in Fig. 2 was taken by a trolley-mounted camera. The hook and suspension cables fill a significant portion of the image, blocking the view of the payload below the hook.

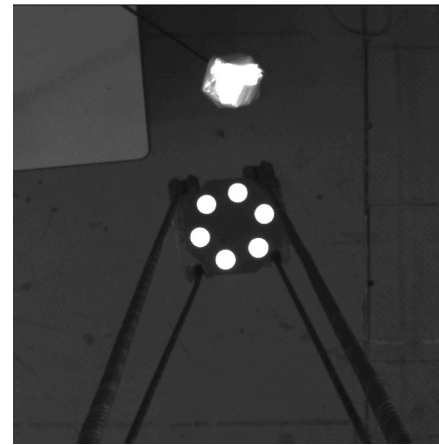


Fig 2. Image from Trolley-Mounted Vision System

Other researchers have used gyroscope-based sensing solutions with some success [16]–[18]. The gyroscopic measurements are often coupled with secondary means of sensing, such as potentiometers measuring cable deflection. Observers are used to smooth the resulting signals. The design and implementation of such observers introduces an additional layer of complexity to the system. 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 or estimator comes additional complexity, design time, failure modes, and cost.

B. Conflict Between Feedback and Human Operators

Another major challenge of implementing feedback control is conflict with human operators. Neglecting the difficulties mentioned above, feedback can work well for pre-planned motions. 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 that provide not only the initial reference command to the crane, but also issue additional commands 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.

III. INPUT SHAPING

Input shaping is a command-filtering 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 3 demonstrates the input-shaping process, using a simple crane model. A series of impulses is convolved in real-time with the original reference command to create a shaped command. In Fig. 3, the original velocity pulse command is transformed into a

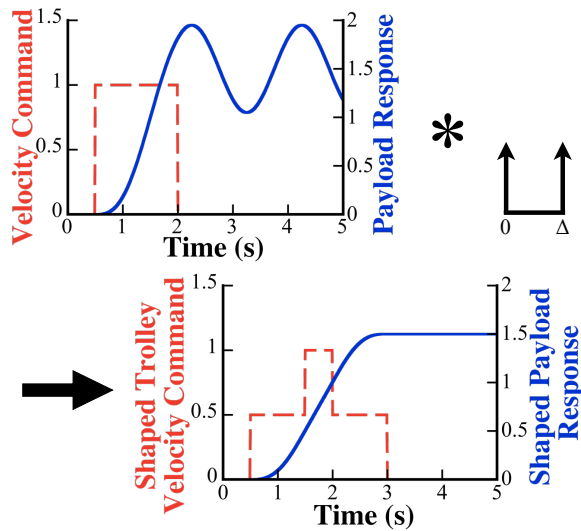


Fig 3. The Input-Shaping Process

staircase command. This shaped command produces much less payload oscillation than the unshaped command.

The amplitudes and time locations of the impulses that compose an input shaper are designed using estimates of the natural frequencies and damping ratios. Input shapers can also 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, estimates of system parameters 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.

IV. CONTROL OF A 10-TON INDUSTRIAL BRIDGE CRANE

Both feedback and input shaping control methods have been implemented on the 10-ton industrial bridge crane in Fig. 4. 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 pendent to a Siemens PLC, which 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. 5 is a conceptual overview of the feedback system implemented on the bridge crane. The machine vision system is used to feed back the hook deflection, θ , to a Proportional-Derivative (PD) controller.

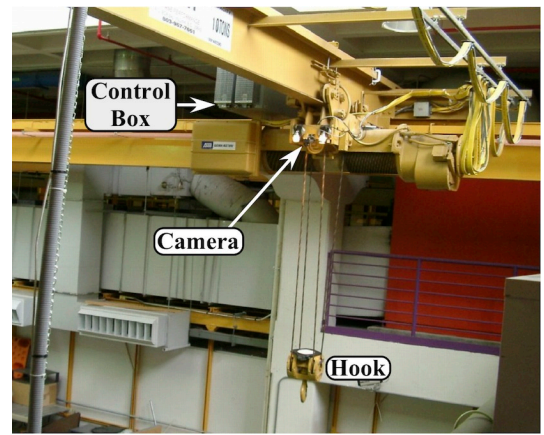


Fig 4. 10-ton Industrial Bridge Crane

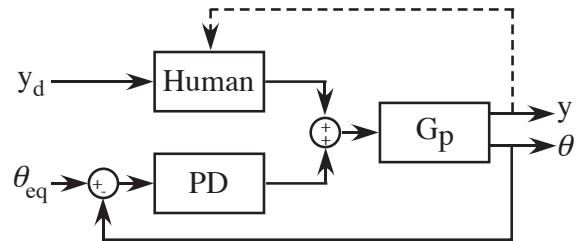


Fig 5. Conceptual Block Diagram of the PD Crane Controller

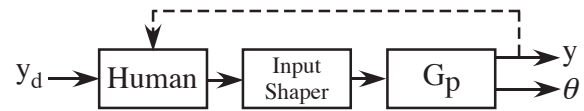


Fig 6. Conceptual Block Diagram of Input-Shaping Controller

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 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 most industrial cranes, such favorable conditions would not exist.

A block diagram of the input-shaping control system is shown in Fig. 6. 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.

A simple, 3m point-to-point move of the 10-ton bridge crane using “manual” control (no feedback or input shaping) is shown in Fig. 7. The hook oscillates around the

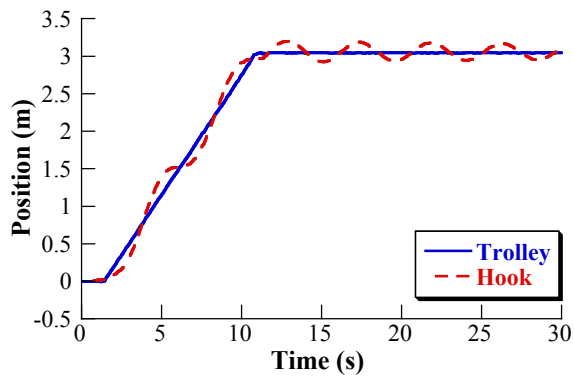


Fig 7. "Manual" Control Point-to-point Move

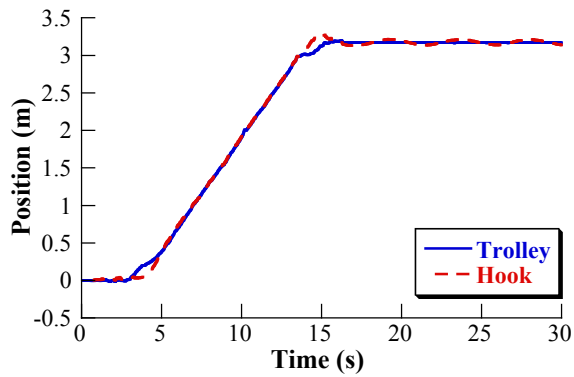


Fig 8. PD-Feedback Control Point-to-point Move

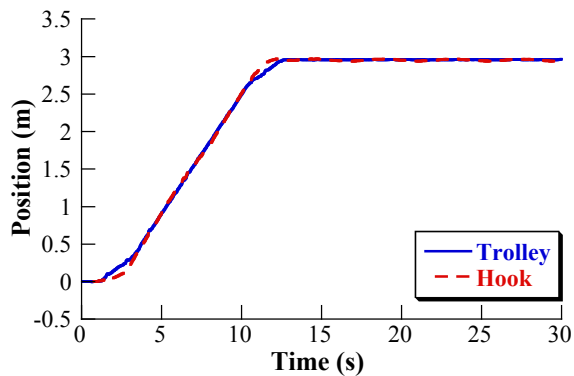


Fig 9. Input Shaped Point-to-point Move

location of the trolley both during the move and after it is completed. This continues for a significant amount of time, unless stopped manually. A similar move using the PD-feedback control system is shown in Fig. 8. The feedback controller greatly reduces the hook oscillation. The input-shaping controller is able to reduce payload oscillation to nearly zero for this move, as shown in Fig. 9. The input-shaped response also has a slightly lower transient oscillation than the PD-Feedback control system. This can be seen in Fig. 10, which shows the hook deflection for the three cases. Both controllers provide significant improvements over the manual control case.

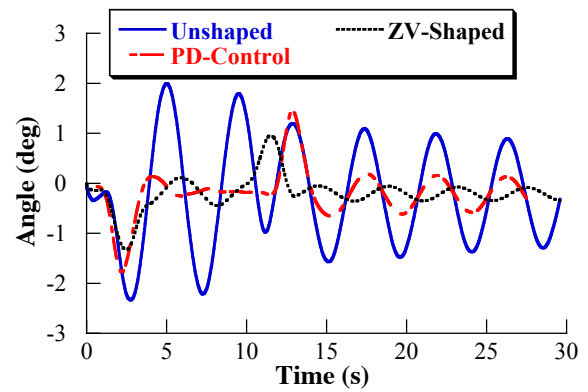


Fig 10. Hook Angle for Point-to-point Moves

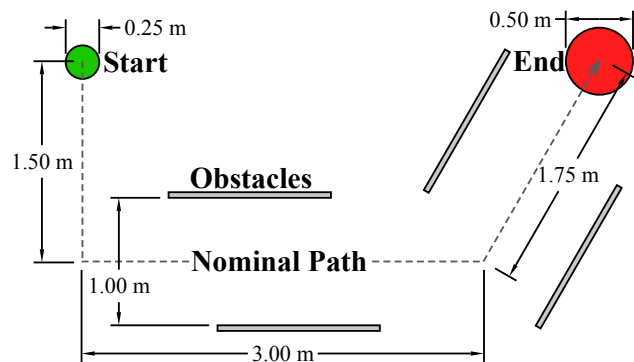


Fig 11. Obstacle Course Used for Operator Study

V. 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 input shaping.

A. Operator Study Protocol

Twelve novice operators were asked to drive the crane through the obstacle course shown in Fig. 11. The task assigned to the operators was to move the crane payload from the 0.25m diameter start circle to the 0.5m diameter target, end circle as quickly and safely as possible. The crane suspension cable length was set to approximately 5.5m, and 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), Zero Vibration (ZV) input shaping, 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. The order of the trials was randomized to help mitigate operator-learning effects.

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 during

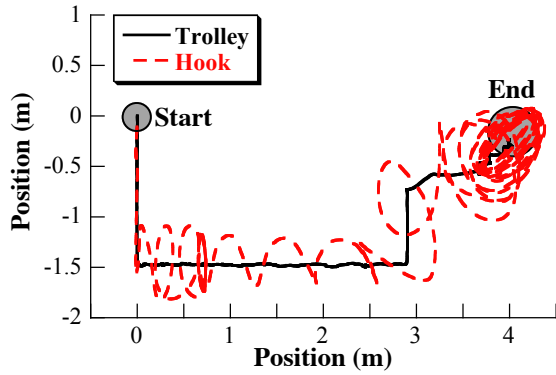


Fig 12. Example Trial with Manual Control

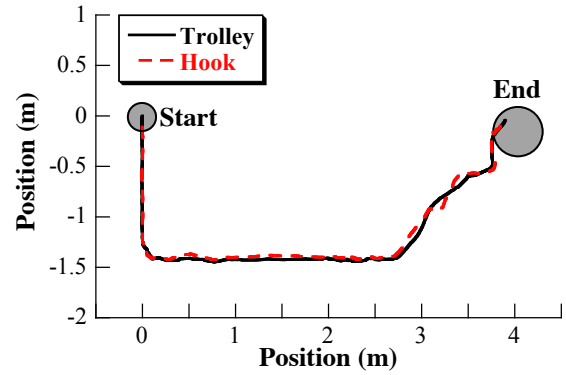


Fig 14. Example Trial with ZV-shaped Control

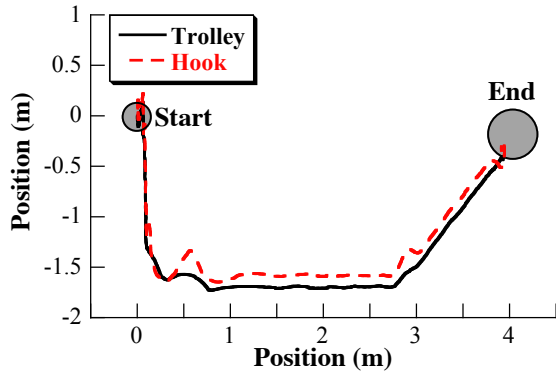


Fig 13. Example Trial with PD-Control

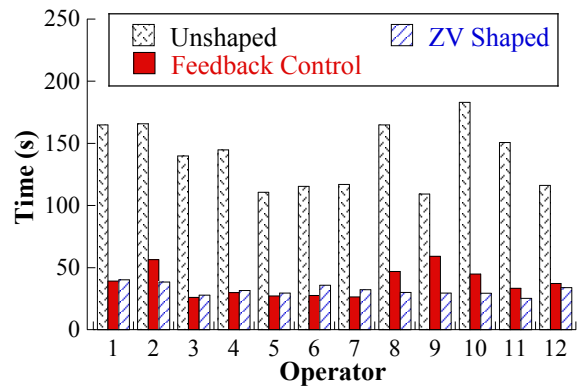


Fig 15. Task Completion Times

each trial was calculated to give an approximation of energy use.

B. Operator Study Results

An example trial with manual control is shown in Fig. 12. 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. The operator required 165s 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. 13. The hook now exhibits much less oscillation, making positioning it within the target region much easier. The trial was completed in 39s, representing a 76% reduction from this operator's completion time with the manual control.

An example trial with the input-shaping controller from the same operator is shown in Fig. 14. 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 40s.

The task completion times for all twelve operators are shown in Fig. 15. The PD controller and input shaping allowed every operator to complete the task more quickly than manual control. The average task completion time for each controller is shown in Fig. 16. The error bars indicate one standard deviation above and below the mean. The

average completion time with PD-control was 74% less than manual control (37s vs. 140s). Input shaping further reduced the average completion time to 32s, representing a 14% reduction from PD control and a 77% 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, $F(2, 33) = 160.83$, $p \ll 0.001$. A paired t-test indicated that differences in completion time between PD-control and input shaping were less statistically significant, $t(22) = 1.63$, $p = 0.12$.

The average total distance the trolley traveled under each control method is shown in Figure 17. The average distance traversed under manual control was 9.52m. This is approximately 3m more than the nominal path through the obstacle course. With PD control, the average travel distance was reduced to 7.84m, a 18% reduction from manual control. The average distance traveled using the input-shaping controller was slightly less, 7.51m. The shorter total travel distance afforded by input shaping provides evidence that it is more energy efficient than either manual control or PD control. A one-way ANOVA confirmed that the differences in travel distance observed between control methods were less statistically significant, $F(2, 33) = 9.52$, $p = 0.06$.

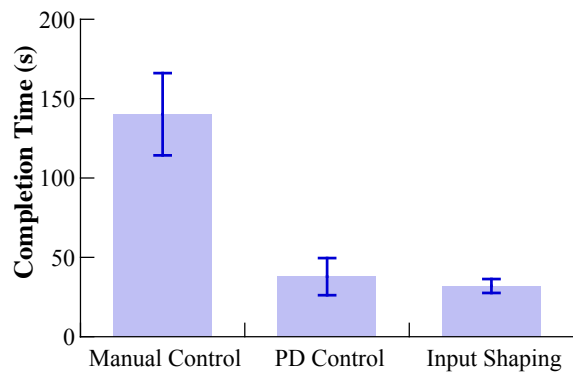


Fig 16. Average Task Completion Times

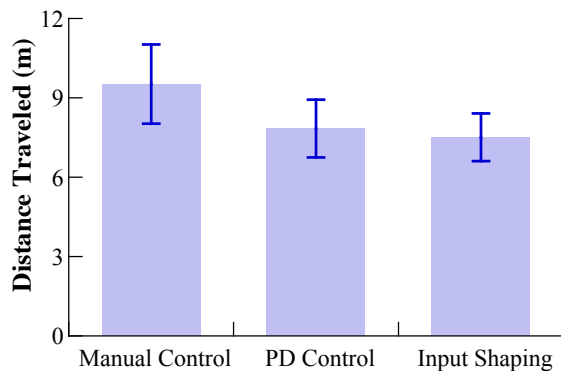


Fig 17. Average Distance Traveled by the Crane Trolley

VI. CONCLUSIONS

This paper discussed the use of feedback controllers and input-shaping controllers on cranes. The difficulties of implementing feedback controllers on cranes were described, including difficulty sensing the payload and human operator compatibility problems. Implementations of feedback control and input shaping on a 10-ton industrial bridge crane were presented. Both feedback control and input shaping significantly reduced oscillation. A study of twelve novice crane operators demonstrated that the reduction in oscillation allowed the operators to more quickly complete crane positioning tasks. Input shaping produced the lowest average task completion times and shortest average trolley travel distance.

ACKNOWLEDGEMENTS

The authors would like to thank Siemens Energy and Automation and Boeing Research and Technology for their support of this work.

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