Advantages of Using Command Shaping
Over Feedback for Crane Control

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Abstract—Cranes are the primary heavy lifters for a wide variety of industries. However, all cranes share the same important limitation on efficiency: payload oscillation. Given the significance of cranes, it is not surprising that a large amount of research has been dedicated to eliminating this oscillation. Much of this research has been directed toward feedback control methods. Another portion of the work has focused primarily on command-shaping methods. This paper explores the problems with using feedback for crane control, which include the difficulty in sensing the crane payload, widely varying system dynamics, and human-operator compatibility. In light of these problems, input shaping is shown to be a favorable solution.

I. INTRODUCTION

Cranes are a vital component of many manufacturing, construction, and shipping port activities. They are the primary heavy lifters employed in numerous industries. As such, improving crane efficiency can have great impact on a wide variety of applications. The primary limiting factor in safe and efficient crane operations is payload swing.

To illustrate this problem, consider the simple 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. The 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. Multi-mode, double-pendulum effects are also seen in this response. The impact of these dynamics on crane control will be discussed later.

Many researchers have employed feedback methods to control payload oscillation. A thorough review of these techniques developed during the 20th century is presented in [1]. However, in this work several critical factors in crane operation are typically neglected. 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). This makes the implementation of any type of feedback method difficult.

Another major factor of crane operation that many researchers ignore 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 also 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 make it difficult to tune the computerized feedback control.
Rather than utilizing sensors and feedback, another control approach is to shape the reference commands being sent to the crane. Input shaping is one such method that reduces payload oscillation by filtering the human-operator commands [2], [3]. This approach has several advantages over feedback methods. The primary advantage is that no computerized feedback is needed. This leaves the human operator as the sole feedback controller.

All that is needed to implement input shaping are estimates of the cranes natural frequencies and damping ratios (which are near zero for most cranes). A major advantage over 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 [3]–[5]. Additionally, input shaping does not create a feedback system that competes with the crane operator. As such, it is compatible with human operators, as supported by the results from numerous crane-operator studies [6]–[10].

This paper will explore the challenges of using feedback for crane control and show that input shaping is a preferable solution for the vast majority of cranes. In the next section, the difficulties of successfully implementing feedback control on cranes are explored. In Section III, the advantages of using input shaping are presented. Example studies of human crane operators are presented in Section IV.

II. CHALLENGES OF USING FEEDBACK ON CRANES

There are three primary obstacles in the successful implementation of feedback control on cranes. One is the difficulty in accurately and robustly sensing the crane payload. The second is that the crane dynamics can vary greatly depending on the crane and payload configurations. The inability to accurately and robustly sense the payload exacerbates this problem, as it makes sensing payload changes (and adjusting the controller accordingly) difficult. The final issue is human-operator compatibility. This section will discuss these three challenges in detail.

A. 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.

There are two methods that have been used with some success: machine vision and gyroscopes. Unfortunately, both of these methods are expensive. Some researchers have proposed vision systems mounted throughout the crane workspace and have shown them to work well in laboratory conditions [11], [12]. Cranes at Georgia Tech [13] and Logan Aluminum [14] 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.

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. 3 was taken by a trolley-mounted camera. The hook and suspension cables fill a significant portion of the image, blocking the payload below.

To demonstrate one of the possible problems with vision systems, consider the responses shown in Fig. 4. The plot shows the trolley and payload position for the crane whose vision system was shown in Fig. 3. There are five points during which the position of the crane hook is lost, or, more precisely, a reflective spot on the floor was interpreted as the hook. In each case, the crane feedback control system attempts to eliminate the (incorrectly interpreted) disturbance. This causes the trolley to move away from the
desired position. Certainly a series of additional checks could be programmed into the control system in an attempt to mitigate this problem. For example, the hook shown in Fig. 3 is equipped with a hexagon pattern of reflective markers to aid in distinguishing it from spurious bright spots. However, this adds even more complexity to the system and is not a failsafe measure.

Other researchers have used gyroscope-based sensing solutions with some success [15]–[17]. In this work, the gyroscopic 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.

B. Crane Dynamics and Their Effect on Feedback Control

In addition to being difficult to sense, crane payloads can create dynamic effects that are difficult to control. Some crane payload configurations create double-pendulum effects [18]. In these circumstances, the controller is now responsible for suppressing two modes of oscillation. If the control system is designed only for the typical, single-pendulum payload configuration, then this can create significant problems, including instability. If the double-pendulum is considered, and the controller is designed to ensure stability for the multi-mode case, then the resulting controller will likely be too conservative for efficient operation with single-pendulum configurations. This will lead to sluggish, sub-optimal performance.

To illustrate this idea, consider the planar model in Fig. 1, under PD feedback control using the hook swing angle, $\phi$, as feedback. The trolley and hook responses for this model with a single-pendulum configuration are shown in Fig. 5. The length of the rigging cable, $l_2$, and the payload mass, $m_p$, are set to zero. The hook closely follows the trolley and hook/payload oscillations are damped fairly quickly after the trolley reaches the final location.

Figure 6 shows the response for the case in which the payload configuration creates double-pendulum effects. In this case the suspension cable length, $l_1$, was chosen identical to that used in Fig. 5, but an additional rigging length, $l_2$, was used to connect the payload. Using the same gains as in Fig. 5, as one might do given the same suspension cable length and inability to sense the payload, the responses in Fig. 6 result. The peak payload oscillation is increased and the oscillation takes much longer to settle to its equilibrium position. The hook has significant oscillations as well.

Another example of this problem is shown in Fig. 7. The plot shows the disturbance responses of a small tower crane [19] for cases where the payload configuration creates single and double-pendulum dynamics. For the single pendulum, the feedback controller, using the hook swing angle as feedback, successfully eliminates the disturbance. However, for the double-pendulum, the feedback controller is unstable. A logical solution to this dilemma would be to use some type of gain-scheduling algorithm. For such an algorithm, significant information must be known about the payload. The dynamics of the double-pendulum case depend on the hook and payload masses, as well as suspension cable and rigging lengths [9], [18], [20]. If a crane is employed at a location that has a fairly limited number of payloads and payload configurations, then a manual gain-scheduling
approach (*i.e.*, the crane operator manually triggering a gain change) might be sufficient. However, many cranes operate in environments where the type of payload varies greatly, making such a manual selection impractical. This, coupled with the fact that the payload parameters cannot be easily sensed, makes automatically assigning gains based upon the current payload impractical as well.

In order to avoid the difficulty of measuring the payload, it is also possible to measure the hook swing angle and design a feedback controller to eliminate the swing by assuming that driving the hook swing angle to zero will stop the payload swing. Figure 8 clearly illustrates the problem with this approach when the payload creates a double-pendulum effect. Both cases show the same hook swing angle, 10 degrees; however, the actual position of the payload is very different. A feedback controller designed simply based on the swing angle may not only function poorly, but can also lead to unstable results.

C. Conflict Between Feedback and Human Operators

Another major drawback of feedback control is conflict with human operators. For pre-designated or point-to-point crane motions, feedback, ignoring the difficulties mentioned above, can work fairly 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 conflict. The human operator provides not only the initial reference command to the crane, but also introduces 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 eliminating swing with manual command shaping.

III. Advantages of Input Shaping

An alternative to feedback methods is command filtering. Input shaping is one such method that has been successfully used to limit crane payload oscillations [6]–[10], [18], [21]. Another, related method uses Infinite Impulse Response (IIR) Filters [22]. Figure 9 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. 9, the original velocity pulse command is transformed into a staircase command. This shaped command produces much less payload oscillation than the unshaped command.

Input shapers are designed using estimates of the systems natural frequencies and damping ratios and can be made robust to changes in these parameters [3]–[5]. In addition, shapers can be designed to account for system nonlinearities [23], [24] and to eliminate multiple modes of vibration [18], [25]–[27]. 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.

Input shaping has many advantages over feedback for crane control. It avoids the complications of having to sense the crane payload. In addition, it will never drive the system unstable, as is possible with feedback methods. 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 [6]–[10], some of which are discussed in more detail in the next section.

IV. Studies of Human Crane Operators

The effects of input shaping on human crane operator performance have been well studied [6]–[10]. The first such studies used a bridge crane with single-pendulum dynamics [6]. Figure 10 shows actual payload trajectories as measured with an overhead vision system while an operator attempted to maneuver the payload to a desired target location. Without input shaping, the operator collided the payload with two of the obstacles. With input shaping enabled, the payload sway was virtually eliminated.
Figure 11 shows the task completion time for 13 operators that navigated the obstacle course shown in Fig. 10. The dark bars represent the unshaped runs, whereas the light bars represent the runs with input shaping enabled. The end time was defined as the moment at which the payload entered the target zone and did not subsequently swing outside the zone. The average time to complete the courses with input shaping was 51s, while the average time for the unshaped runs was 135s. In other words, input shaping decreased the completion time by 62%.

A. Slender-Beam Payload Operator Study

Studies conducted with double-pendulum payloads have shown similar improvements from input shaping. One such study used the crane and slender beam payload shown in Fig. 12. The payload creates a double-pendulum effect that is very challenging to control [7]–[9]. To drive the crane, the operators used a standard crane pendant with six directional buttons. The payload was initially suspended 18cm off the ground. The goal for each task was to drive the payload from a 0.5m square to the 0.75m diameter circle, 2m away. The task completion time, hook movement, and operator effort were recorded. The task completion time was measured from when the operator first pushed a button on the control pendant until the payload settled to within the target zone. The operator effort was measured by the number of pendant button pushes required to transport the payload. The operators completed the course without input shaping, using a two-mode Zero Vibration (ZV) shaper [27], and using a two-mode Specified Insensitivity (SI) shaper [18].

The hook response during some typical moves around the obstacle is shown in Fig. 13. The figure shows that without input shaping, the system oscillates a great deal, but both input shapers successfully suppress the hook oscillation. The average completion time for the 17 tested operators without input shaping was 149s. For both shapers tested, the average completion time was reduced to only 22.5s, or 15% of the time required without input shaping.

Figure 14 shows the number of button pushes required to move the payload around the obstacle. Without input shaping, the operators needed an average of 33 button pushes to complete the task. With shaping enabled, the average number of button pushes decreased to only 5, an 85% reduction in operator effort.

The tests were conducted to determine the effects of input shaping on low- to moderately-skilled operators. To give some insight into their effect on highly-skilled operators, a crane operator with 30 years of experience was recruited.
to drive the crane for 1 hour and perform a wide range of performance tests. Without input shaping, the operator took 33s to move the payload around the obstacle and into the target zone. This is 47% slower than the average time of 22.5s when input shaping was enabled for the low-to-moderately skilled operators. Furthermore, the payload driven by the expert had significant residual oscillation; it swung from one edge of the target circle to the other. With input shaping enabled, the skilled operator completed the move in only 27s. In this case, the residual oscillation was only about 1-2 inches. When asked to evaluate the performance of input shaping, the expert operator repeatedly stated, “It is very smooth.”

V. CONCLUSIONS

Significant research using feedback control to eliminate crane payload oscillations has been conducted. However, there are significant obstacles toward application of this work, including the difficulty of accurately and reliably sensing the payload and its states, widely varying crane dynamics, and human-operation compatibility. Input shaping is another control method that can be used to eliminate crane payload oscillations and has none of these deficiencies. Sensing the payload motion is not necessary. It can be also made robust to varying system dynamics. Furthermore, input shaping has been shown to be compatible with human operators through a significant number of crane-operator studies.

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REFERENCES


Fig 14. Operator Effort