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Experimental Comparison of Manual and Automated Crane Control Through Obstacle Fields

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Abstract— **Movement of bridge crane payloads through a crowded workspace requires small levels of payload swing for safe operation. The importance of limiting payload swing in such environments was evaluated by studying operator navigation through an obstacle field. Performance under manual operation with and without input shaping was compared with automated traversal using pre-programmed trajectories. These control strategies and test subjects' design and navigation approaches were compared using a small-scale bridge crane. During the navigation tests investigated, the system begins as a single-pendulum and becomes a double-pendulum upon pick up of a payload introducing additional complexity to system control. While implementation of input shaping reduced collisions during manual operation, variance in path selection and shaper design yielded a range of completion times. Implementation of pre-programmed trajectories reduced completion times; however, the lack of human oversight introduced the risk of failing to deposit the payload at the correct location.**

I. INTRODUCTION

Cranes are complex machines commonly used in dangerous environments that require the movement of heavy payloads. Unfortunately, crane motion often leads to large payload oscillations that reduce safety, increase task completion time, and lead to payload positioning inaccuracy. For single pendulum systems, experienced crane operators may eliminate some payload swing by inducing oscillation that cancels existing oscillation. However, some operations may require the operator to pick up a payload creating a double-pendulum system. The behavior of these double-pendulum systems makes it difficult to effectively reduce vibration with manual command shaping.

A variety of control techniques have been proposed for reducing oscillation. Smooth commands have been proposed to reduce excitation of system flexible modes [1] [2]. However, this approach tends to incur large rise-time penalties [3]. Feedback control has also been suggested for suppression of double-pendulum dynamics [4] [5]. More recently, a quasi-PID controller has been suggested for underactuated double-pendulum systems [6]. However, feedback control can be difficult to implement as it can be challenging to accurately measure payload motion.

Work by Singer and Seering demonstrated that input shaping can reduce residual vibration in linear vibratory systems [7]. This method convolves a sequence of impulses, called an input shaper, with the reference command input. The resulting shaped command is then used to drive the system. The timing and amplitude of the impulses in the series impacts the transient and residual vibration of the vibratory system. With accurate knowledge of system parameters, such as natural frequency and damping ratio, it is possible to obtain a sequence of impulses that eliminates residual vibration at the expense of a small increase in rise time. Fig. 1 shows the response of a linear second order system to unshaped (solid line) and shaped (dashed line) step inputs.

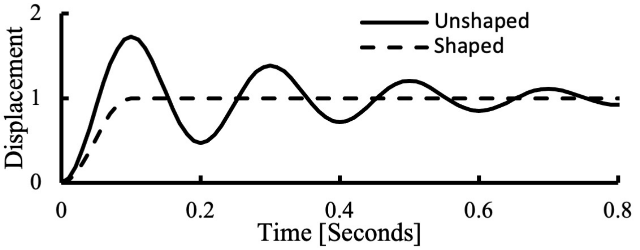

Fig. 1. Response of a linear second order underdamped system to an unshaped step command (solid line) and an input shaped step command (dashed line).

While previous crane operator studies have primarily focused on operation of either single or double pendulum systems [8] [9] [10], this study examines a scenario where the system changes from a single-pendulum to a double-pendulum during the course of operation.

The first set of trials presented by this paper examines the design strategies employed by teams of graduate students to safely navigate a bridge crane payload through the obstacle course shown in Fig. 2. First, operators were tasked with navigating the course manually without the assistance of a controller. The second trials required navigation of the course with the assistance of a single input shaper. The third trial used a preprogrammed trajectory to complete the course without direct human control.

The second set of trials looks to examine the difference in controllability of the system in single and double-pendulum states for manual operation with and without the assistance of an input shaper.

The next section introduces the various input shapers employed during the testing. Section 3 describes the experimental protocol used to direct teams of graduate students to develop and test the various crane controllers. The methodology is based on using a crane-driving contest to encourage the best possible control strategies. Section 4 presents the results of the crane-driving contest. Section 5 presents results from measuring the operator effort required to drive the crane using various controllers. Section 6 presents the conclusions.

II. INPUT SHAPING

The earliest input-shaping technique, "posicast" control, broke commands into two smaller magnitude commands, one

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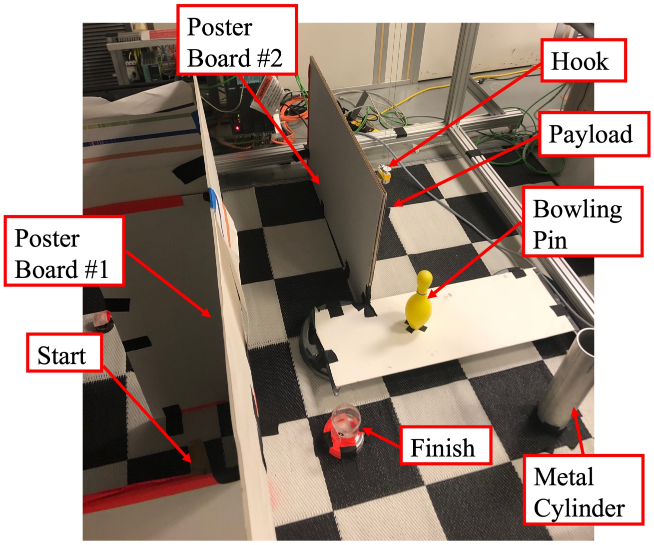

Fig. 2. Obstacle course.

of which was delayed by one half period of the system's natural frequency [11]. This technique is known as zero-vibration (ZV) shaping because the constraint equation used to calculate the command components ensures there will be zero residual vibration if the system is modeled accurately. This ZV shaper is a two-impulse shaper given by [7] [11]:

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & 0.5T_d \end{bmatrix} \tag{1}$$

where T_d is the damped period of oscillation:

$$T_d = \frac{2\pi}{\omega_n \sqrt{1-\zeta^2}} \tag{2}$$

where ω_n is the natural frequency and ζ is the damping ratio, and K is a unitless variable defined by:

$$K = e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}} \tag{3}$$

The ZV shaper has a short rise time compared to other shapers, but is sensitive to modeling errors. The zero-vibration and derivative (ZVD) shaper given by [7]:

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{(1+K)^2} & \frac{2K}{(1+K)^2} & \frac{K^2}{(1+K)^2} \\ 0 & 0.5T_d & T_d \end{bmatrix} \tag{4}$$

provides additional robustness to modeling errors at the cost of additional rise time. Unlike the aforementioned shapers which force vibration to zero at a specified frequency, the extra-insensitive (EI) shaper simply constrains the vibration to be below some tolerable level [12].

Although the ZVD and EI shapers provide additional robustness to frequency error, some multi-mode systems such as the double-pendulum system in this experiment may have higher frequency modes that are not sufficiently reduced by a robust single mode shaper. A number of methods have been developed for obtaining shapers that suppress multiple vibration modes. One approach uses the convolution of multiple single mode shapers [13].

A second approach to designing a multi-mode shaper is the simultaneous solution of the vibration constraint equations for multiple modes [13]. Although this approach often requires an optimization program to determine impulse times and amplitudes, the resulting shaper always produces a faster rise time than a convolved shaper.

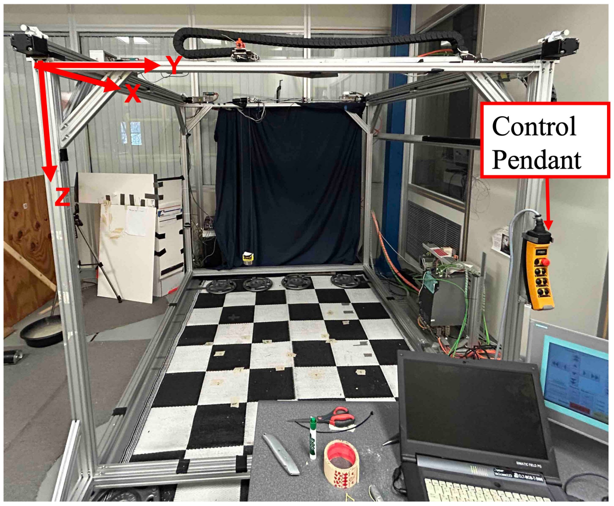

Fig. 3. Miniature bridge crane.

More aggressive shaped commands may be obtained via the inclusion of negative impulses in the input shaper. For the shaper amplitudes to sum to 1 the amplitudes of the positive impulses must be increased to account for the addition of a negative impulse. The addition of a negative impulse also decreases the duration of the shaper. One approach to negative shapers is to limit the impulse amplitudes to 1 and -1 [14]. These unity magnitude (UM) shapers can be convolved with a wide range of unshaped inputs without causing actuator saturation. Another approach is to specify the amplitude of the negative impulses. These specified-negative-amplitude (SNA) shapers span the performance gap between positive and UM shapers [15].

III. METHODOLOGY

Teams of three mechanical engineering graduate students were tasked with using a small-scale bridge crane, seen in Fig. 3, to navigate an obstacle course. During manual operation, the hand-held control pendant was used to drive the three Cartesian axes of the crane. To begin the course, the hook was traversed from the starting point to the payload, as shown previously in Fig. 2. Once the hook was positioned above the payload, a magnet would attach to the bottom of the hook. The payload was attached to the magnet by a string creating the double-pendulum, as seen in Fig. 4. To complete the course the payload was transported to the finish location depicted in Fig. 2 and lowered into a target container. Subjects were able to drive the hook and payload both over and around obstacles as necessary to complete the course.

The hook had a mass of 0.658 kg, while the magnet and the payload had masses of 0.005 kg and 0.07 kg, respectively. The suspension length between the hook and the payload was 0.7 m. The suspension length of the hook was controllable within a range of 0.58 m to 1.86 m. For the single-pendulum, these values resulted in a mode ranging from 2.3 rad/s to 4.11 rad/s. While for the double pendulum, these values

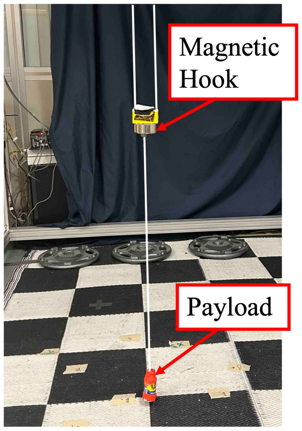

Fig. 4. Double-pendulum payload configuration.

resulted in a low mode ranging from 2.24 rad/s to 3.41 rad/s and a high mode range from 4.04 rad/s to 4.75 rad/s. The damping ratio of the single and double-pendulum systems was approximated as 0.001. The velocity was limited to 0.1 m/s along the bridge axis and 0.2 m/s along the trolley axis. The trolley was able to accelerate along the bridge and trolley axes at 1 m/s^2. The hoist axis speed was limited to 0.08 m/s and an acceleration of 1 m/s^2.

The first set of trials focused on safe and fast completion of the obstacle course. These trials consisted of three different control approaches:

1) manual
2) input-shaped manual
3) pre-programmed trajectories

To encourage safe operation of the system, five second time penalties were added to the completion time for each contact with an obstacle up to a maximum of 10 seconds per obstacle. Knocking over the bowling pin obstacle incurred a ten second penalty. In addition, dragging the payload across the floor or against an obstacle also earned a 10 second penalty.

The teams were charged with developing a single input shaper to aid their manual operation. To achieve fast completion times, with minimal incurred time penalties, teams had to strike a balance between shaper robustness to cancel out both single and double-pendulum swing, and shaper duration.

For the pre-programmed trajectories teams developed a matrix of time and associated trolley and hoist velocity commands. These command matrices were convolved with input shapers chosen by the teams to minimize hook and payload oscillation.

A second set of trials focused on the impact input shapers had on operator effort and controllability of the system during manual operation. Pre-programmed trajectories were not tested. Similarly to the first set of trials, the teams were tasked with navigating the system to a payload, picking up the payload, and depositing the payload at a tertiary location. However, for this set of trials no time penalty was incurred for collision with obstacles.

TABLE I
COURSE COMPLETION AND TIME PENALTIES FOR THE MANUAL UNSHAPED OPERATION.

Team	Completion Time	Penalty Time	Total Time
1	1:31	0:30	2:01
2	2:13	0:35	2:48
3	1:23	0:20	1:43
4	2:04	0:25	2:29
5	1:21	0:10	1:31
6	1:39	0:10	1:49
Average	1:41.8	0:21.7	2:03.5

IV. RESULTS

A. Manual Unshaped Operation

The oscillatory nature of the system made unshaped control difficult yielding the long completion times and large time penalties seen in Table I. The average total completion time, with penalties, was 2:03.5, while the standard deviation was 29.4 seconds.

The large variation in completion times is indicative of the importance of operator skill when controlling single and double-pendulum systems. However, path selection also impacts the speed at which the task can be completed. A common approach used for the manual operation without input shaper assistance was hoisting the hook up so that the hook could pass over obstacles. Although the vertical movements resulting from this strategy comes at the cost of longer movement times, it effectively eliminates the risk of colliding with obstacles. In addition, the reduction in suspension length yields decreased hook swing. Only one team navigated the course at the starting suspension length of 1.85 m. Although they were able to successfully navigate from the starting position to the payload without colliding with an obstacle, the hook experienced large deflections. The other five teams chose to maneuver up and over the second tall poster board and then lower the hook down to the payload. This path choice, along with the increased complexity in controlling double-pendulum systems, led to a total of nine collisions during the single-pendulum portion of the manual unshaped operation trials for all teams, while a total of sixteen collisions occurred during the double-pendulum portion of the task.

Ineffective payload lift also contributed to the difficulty in controlling the double-pendulum system. Attempting to attach the payload while large hook oscillations persisted led four teams to knock over the payload in their attempts to connect with the magnetic hook. By hoisting the payload without orienting the hook directly over the payload, the four teams with the largest time penalties experienced large levels of deflection in the double-pendulum portion of the task. Each of these teams collided with obstacles three times during the double-pendulum phase. On the other hand, the two teams with the fewest time penalties took time to position the hook accurately above the payload before hoisting and were able to navigate the double-pendulum phase of the course without colliding with obstacles.

One method employed by a team to stop oscillation of the double-pendulum was to drag the payload along the second tall poster board. While this approach incurred a ten second

TABLE II

COURSE COMPLETION AND TIME PENALTIES FOR THE MANUAL SHAPER-ASSISTED OPERATION.

Team	Completion Time	Penalty Time	Total Time
1	1:14	0:00	1:14
2	1:56	0:00	1:56
3	0:51	0:00	0:51
4	1:32	0:10	1:42
5	0:50	0:00	0:50
6	1:14	0:00	1:14
Average	1:16.1	0:01.7	1:17.8

TABLE III

COURSE COMPLETION AND TIME PENALTIES FOR THE PRE-PROGRAMMED TRAJECTORY TRIALS.

Team	Completion Time	Penalty Time	Total Time
1	1:05	0:00	1:05
2	0:43	0:00	0:43
3	0:35	0:20	0:55
4	0:47	0:00	0:47
5	0:57	0:00	0:57
6	0:51	0:20	1:11
Average	0:48.2	0:06.6	0:54.8

penalty, it enabled a shorter path and yielded the second shortest completion time in this trial. All six teams allowed the payload to collide with the exterior of the target container to damp out swing before attempting to deposit the payload.

B. *Manual Shaper Assisted Operation*

The application of input shaping to the manual operation of the crane yielded reduced completion times and smaller time penalties, as seen in Table II. Among the six teams, only two time penalties were incurred during the shaper assisted manual operation, down from twenty-five in the unshaped manual operation trials. The average penalty time dropped from 21.6 seconds in the unshaped case to 1.6 seconds for the input shaper tests.

Although all teams had marked improvements in completion time and obstacle avoidance, the input shaper design strategies employed varied significantly. The longest and most robust shaper employed was a two-mode ZVD shaper with a duration of 3.64 seconds, designed to eliminate the double-pendulum modes. Team 2 opted to pass over the bowling pin obstacle during both single and double-pendulum operation rather than navigate between either the bowling pin and the second vertical poster board or the bowling pin and the metal cylinder.

Team 1 followed a similar path during the traversal from the starting position to the payload; however, during the double-pendulum phase of the course they opted to pass between the bowling pin and metal cylinder obstacles. The shaper implemented by team 1 was a two-mode ZV shaper with a duration of 1.78 seconds obtained through direct solution of vibration constraints.

The only time penalties incurred during the input shaper assisted manual operation trials were during the double-pendulum portion of the course. The operator in this instance took a wide berth around the bowling pin and the payload collided with the metal cylinder twice. This decrease in the number of collisions is indicative of the increased ease of control and reduced oscillation when an input shaper is applied to the system.

In addition to the reduction in number of collisions, the implementation of input shapers enabled operators to maneuver the hook at longer suspension lengths without introducing large oscillations. This is evident by the reduction in the number of operators maneuvering up and over tall obstacles while traversing from the starting position to the payload pickup location. Five operators used this strategy in the unshaped trials, but only one in the shaper assisted trials. This path selection strategy resulted in a significant disparity in completion times between team 4 and team 5 even though both teams implemented single-mode ZV shapers with durations of approximately 1 second.

Team 5 completed the course in the shortest time following a similar path to team 2 using a less robust shaper with a shorter duration. However, as a result of the lower robustness of the single-mode ZV shapers, teams 4 and 5 experienced larger payload oscillations upon reaching the target container. To compensate for these oscillations operators from these two teams allowed the payload to collide with the exterior of the container to reduce payload swing before delivering the payload into the container.

The final two teams both implemented robust single-mode EI shapers to reduce hook and payload oscillation. Team 6 implemented an EI shaper with a duration of 1.66 seconds. The resulting shaper has a similar duration to the two-mode ZV shaper employed by team 1. Thus, as these teams followed similar paths during navigation of the course and implemented shapers with similar durations it is unsurprising that the completion times were similar.

The EI shaper chosen by team 3 was designed to eliminate oscillation resulting from the first vibration mode of the double-pendulum. Although the shaper chosen by team 3 had the second longest duration at 2.17 seconds, the path selection of the operator resulted in completion of the obstacle course in the second shortest time.

In addition to the increase in viable path selection options resulting from the implementation of input shapers, the reduction in hook oscillation during single-pendulum operation also enabled operators to accurately position the hook above the payload with little residual oscillation. Thus, operators were able to hoist the payload from its initial location without introducing large amounts of oscillation in the double-pendulum system.

C. *Pre-programmed Trajectory*

The removal of direct human control in the pre-programmed trajectory trials resulted in shorter completion times compared to both the unshaped manual operation and the input shaper assisted manual operation trials, as seen in Table III. On average, the pre-programmed trajectories were 27.6% faster than the average input shaper assisted manual operation completion times and 54.4% faster than the average unshaped manual operation trial.

However, the implementation of the pre-programmed trajectories and removal of human control also introduced the possibility that the payload would not be delivered to the correct location if there were errors in the programmed trajectory. Due to errors in the design trajectories of two teams, the payload collided with the outside of the payload container, rather than being deposited within the container. Twenty seconds were added to the time at which the team collided with the outside of the container as a penalty for missing the payload delivery location.

Two teams implemented several hoist and lower movements into their trajectory to ensure the payload ended in the container. This technique was beneficial for team 1 who initially missed the container. However, for team 4, who initially successfully delivered the payload to the container in 38 seconds, this technique proved to be detrimental adding 9 seconds to the completion time.

Path selection once again played an important role in minimizing completion time. The three teams with the shortest completion times navigated between the bowling pin and second poster board. On the other hand, the three slowest teams either opted to navigate over the bowling pin or between the pin and metal cylinder in both directions of travel resulting in larger course completion times.

The fast completion times is also due in part to the implementation of different input shapers for the single and double-pendulum portions of the task. Teams 1 and 2 convolved the pre-programmed trajectory with a single-mode ZV shaper during the single-pendulum phase and implemented a two-mode ZV shaper during the double pendulum phase. These shapers were respectively 36% and 50% the duration of the two-mode ZVD shaper employed by team 2 in the input shaper assisted manual operation trials, contributing to the significant reduction in completion time for the pre-programmed trajectory trial.

The completion time for the pre-programmed trajectory of team 5 was actually longer than their input-shaped manual trial. This can be partially attributed to the implementation of two different shapers for the single and double-pendulum phases of operation. While the single-mode ZV shaper employed for the single-pendulum phase was similar for both trials, the two-mode ZV shaper employed in the double-pendulum phase of the pre-programmed trajectory was over twice the duration of the shaper implemented in the input shaped manual operation trial.

Both teams 4 and 6 implemented an UMZV shaper with a duration of 0.87 seconds for the single-pendulum phase of the automated control trial. The duration of this shaper is 80.7% and 52.3% the duration of the shapers employed by these teams respectively in the shaper assisted trial. For the double-pendulum phase team 4 implemented a two-mode SNA shaper, while team 6 employed a single-mode EI shaper. These shapers had 28.1% and 10.7% increases in shaper duration compared to the shapers used in the input shaped manual operation trial.

For the pre-programmed trial team 3 implemented the same shaper as the input shaped manual operation trial. Without the 20 second penalty incurred as a result of failing to deposit the payload within the container the pre-programmed trajectory would have navigated the field in 35 seconds, 16 seconds faster than manual operation with the same shaper.

TABLE IV

INPUT CHANGES DURING SINGLE PENDULUM PHASE OPERATION FOR UNSHAPED AND INPUT SHAPER ASSISTED MANUAL OPERATION.

Team	2	3	4	5	6	Mean
Unshaped X-Axis Control	43	49	19	20	39	34
Shaped X-Axis Control	12	14	17	11	24	15.6
Unshaped Y-Axis Control	41	22	33	17	26	27.8
Shaped Y-Axis Control	34	20	17	10	45	27.2
Unshaped Z-Axis Control	24	16	17	20	30	22
Shaped Z-Axis Control	15	8	22	7	26	15.6

TABLE V

INPUT CHANGES DURING DOUBLE-PENDULUM PHASE OPERATION FOR UNSHAPED AND INPUT SHAPER ASSISTED MANUAL OPERATION.

Team	2	3	4	5	6	Mean
Unshaped X-Axis Control	16	7	12	9	18	12.4
Shaped X-Axis Control	15	29	13	9	4	14
Unshaped Y-Axis Control	20	40	17	6	45	25.6
Shaped Y-Axis Control	9	13	8	20	4	10.8
Unshaped Z-Axis Control	22	47	61	14	22	33.2
Shaped Z-Axis Control	28	41	14	13	22	23.6

D. *Effect of Input Shaping on Controllability*

An additional series of tests were performed investigating the amount of operator effort required to navigate the course with and without the assistance of input shapers. The falling and rising edges of the user input commands were tracked and recorded for manual operation with and without the assistance of an input shaper and are shown in Table IV for the single pendulum operation phase. Similarly, Table V shows the total changes in button state for the double-pendulum operational phase. While the average number of user command state changes was smaller in the input shaper assisted case than the unshaped manual operation case there was large deviation in the results. This is likely a result of differences in individual user skill and pathing chosen by the operator. These pathing differences can be seen in Fig. 5 where the trolley and hook locations of one team are plotted in the xy plane for the unshaped manual operation trial and Fig. 6 where the trolley and hook locations are shown for the shaper assisted manual operation trial.

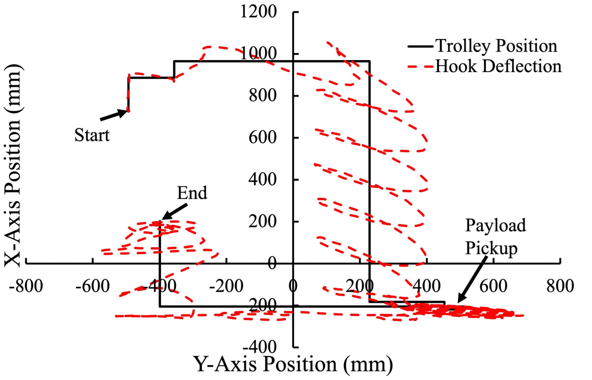

Fig. 5. Trolley and hook position in the xy plane for team 5 during the unshaped manual operation controllability trial.

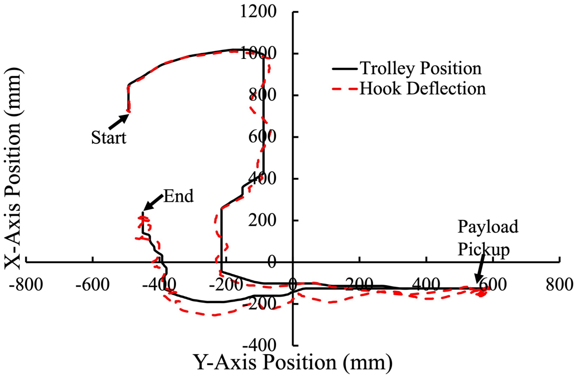

Fig. 6. Trolley and hook position in the xy plane for team 5 during the shaper assisted manual operation controllability trial.

TABLE VI
UNSHAPED MANUAL OPERATION RMS DEFLECTION ALONG THE X- AND Y-AXES.

Team	2	3	4	5	6
X-Axis deflection [mm]	39.1	49.19	46.66	51.33	52.9
Y-Axis deflection [mm]	46.75	44.17	36.72	100.98	39.01

In addition, rms values were calculated for hook deflection along the x- and y-axes under unshaped manual operation as seen in Table VI. While the rms deflection values for the input shaper assisted manual operation trials are shown in Table VII. Along the x-axis the average rms deflection decreased from 47.84 mm in the unshaped manual operation trials to 27.46 mm in the input shaper assisted manual operation trials. While along the y-axis the average rms deflection decreased from 53.53 mm in the unshaped manual operation trials to 20.89 mm in the shaped assisted manual operation trials. These are 42.6% and 61.0% reductions in rms deflection respectively.

V. DISCUSSION AND CONCLUSIONS

This paper investigated and compared different control strategies for moving a crane payload through an obstacle field with single and double-pendulum swing dynamics. Successful navigation through the obstacles with unshaped manual operation heavily relied on operator skill and the chosen strategy. To minimize hook and payload deflection operators reduced the hook suspension length at the cost of additional movement time. Double-pendulum operation proved more difficult to control resulting in 16 collisions compared to the 9 that occurred during the single-pendulum phase of the unshaped manual operation.

Course completion times improved drastically with the implementation of input shapers, dropping from an average total time of 2:03.5 in the unshaped manual operation trials to an average of 1:17.8 in the input shaper assisted manual operation trials. Pathing and input shaper design played a key role in completion of the input shaper assisted manual operation trials with times ranging from 0:50 to 1:56. In addition, the average penalty time also dropped from 29.4 seconds to 1.6 seconds. This improvement stemmed from the reduced hook and payload oscillation resulting from the implementation of input shapers to modify the operator commands.

TABLE VII
INPUT SHAPER ASSISTED MANUAL OPERATION RMS DEFLECTION ALONG THE X- AND Y-AXES.

Team	2	3	4	5	6
X-Axis deflection [mm]	25.47	23.88	37.34	22.97	27.63
Y-Axis deflection [mm]	15.15	18.73	26.02	15.05	29.48

In addition to the reduction in rms hook deflection along the x- and y-axes, the implementation of input shapers reduced the number of button state changes during manual operation. Although there was large deviation in the number of state changes between operators and trials, this was likely a result of differences in user skill and the pathing choices employed by the operators.

While the implementation of pre-programmed trajectories further reduced the average total course time to 0:56.3, the removal of direct human supervision and lack of feedback control resulted in two teams failing to deposit the payload into the target container.

REFERENCES

[1] P. Meckl and R. Kinceler, "Robust motion control of flexible systems using feedforward forcing functions," *IEEE Transactions on Control Systems Technology*, vol. 2, no. 3, pp. 245–254, 1994.

[2] J. L. Wiederrich and B. Roth, "Dynamic synthesis of cams using finite trigonometric series," *Journal of Engineering for Industry*, vol. 97, pp. 287–293, 02 1975.

[3] N. Singer, W. Singhose, and W. Seering, "Comparison of filtering methods for reducing residual vibration," *European Journal of Control*, vol. 5, no. 2, pp. 208–218, 1999.

[4] S. Tanaka and S. Kouno, "Automatic measurement and control of the attitude of crane lifters: Lifter-attitude measurement and control," *Control Engineering Practice*, vol. 6, no. 9, pp. 1099–1107, 1998.

[5] S. Lahres, H. Aschemann, O. Sawodny, and E. Hofer, "Crane automation by decoupling control of a double pendulum using two translational actuators," in *Proceedings of the 2000 American Control Conference. ACC (IEEE Cat. No.00CH36334)*, vol. 2, pp. 1052–1056 vol.2, 2000.

[6] N. Sun, T. Yang, Y. Fang, Y. Wu, and H. Chen, "Transportation control of double-pendulum cranes with a nonlinear quasi-PID scheme: design and experiments," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 49, no. 7, pp. 1408–1418, 2019.

[7] N. C. Singer and W. P. Seering, "Preshaping command inputs to reduce system vibration," *J. of Dynamic Sys., Measurement, and Control*, vol. 112, pp. 76–82, 1990.

[8] D. Kim and W. Singhose, "Performance studies of human operators driving double-pendulum bridge cranes," *Control Engineering Practice*, vol. 18, no. 6, pp. 567–576, 2010.

[9] J. Vaughan, A. Karajgikar, and W. Singhose, "A study of crane operator performance comparing PD-control and input shaping," in *Proceedings of the 2011 American Control Conference*, pp. 545–550, 2011.

[10] A. Kivila, C. Porter, and W. Singhose, "Human operator studies of portable touchscreen crane control interfaces," in *2013 IEEE International Conference on Industrial Technology (ICIT)*, pp. 88–93, 2013.

[11] O. J. M. Smith, *Feedback Control Systems*. New York: McGraw-Hill Book Co., Inc., 1958.

[12] W. Singhose, W. Seering, and N. Singer, "Residual vibration reduction using vector diagrams to generate shaped inputs," *Journal of Mechanical Design*, vol. 116, pp. 654–659, 06 1994.

[13] W. Seering, W. Singhose, and E. Crain, "Convolved and simultaneous two-mode input shapers," *IEE Proc.-Control Theory and Application*, vol. 144, pp. 515–520, November 1997.

[14] W. E. Singhose, W. P. Seering, and N. C. Singer, "Time-optimal negative input shapers," *Journal of Dynamic Systems, Measurement, and Control*, vol. 119, pp. 198–205, 06 1997.

[15] W. Singhose, E. Ooten Biediger, Y.-H. Chen, and B. Mills, "Reference command shaping using specified-negative-amplitude input shapers for vibration reduction ," *Journal of Dynamic Systems, Measurement, and Control*, vol. 126, pp. 210–214, 04 2004.