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IMPROVING MANUAL CONTROL OF TWO-LINK PENDULUM ON GANTRY CRANE WITH ANTI-DELAY CLOSED-LOOP INPUT SHAPING

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ABSTRACT

This paper presents a novel and improved technique in manual control of flexible systems. Flexible systems, when subject to a rapid movement commanded by a human operator, exhibit severe oscillation, causing low positioning accuracy, high fatigue to the human operator, and unsafe accidents. Input shaping filter was proposed to reduce this oscillation by using the destructive interference principle where impulse responses cancel one another resulting in zero residual vibration. Recently, the input shaping filter was placed inside the feedback loop, so-called closed-loop signal shaping, to assist with the manual control of the flexible systems. The vibration was successfully suppressed. However, the input shaping filter also introduced time delays in the feedback loop, which limit the performance of the human operator. This paper offers a breakthrough idea by introducing an anti-delay algorithm called Smith predictor inside the feedback loop. When the plant model is perfect, it can be shown that the Smith predictor can entirely remove the effect of time delay from the feedback loop; therefore, improving the performance of the human operator. Experiments on manual control of a two-link pendulum on a gantry crane show the effectiveness of the proposed algorithm. The human operator was able to move the two-link pendulum with minimum residual vibration. Comparing to the currently world-best technique, the proposed technique could achieve faster maneuvering time, higher accuracy, and with less subjective difficulty.

INTRODUCTION

Flexible systems vibrate severely when they are commanded to move from point to point rapidly. To understand what are meant by flexible systems, Fig. 1 contains several flexible systems, ranging from elevator with flexible sling, cranes with swinging payload, car wiper with elastic joint, wave having oscillatory dynamics, robot manipulators with flexible link or flexible joint, helicopter having swinging payload, coordinate measuring machine (CMM) with flexible probe, industrial robot with intrinsic elastic property, flexible dynamic between cars in car platoon, spacecraft having flexible appendages, and hard disk read/write head with flexible gimbal. Recent applications of input shaping includes biped walking robot by Yi et al. [1], in which the input shaping was applied to shaping of the reference trajectory of the zero momentum point for a full-size humanoid robot. Khodambashi et al. [2] applied the ZVD input shaper to a 3rdArm supernumerary robotic limb platform, which is a 4 DOF robotic arm that is attached to the human's shoulder to help the human drummer to perform complicated rhythms. Zou et al. [3] applied the ZV and ZVD input shapers to a circular dielectric elastomer actuator (DEA) to almost completely eliminate transient vibration and overshoot of the DEA under a step input voltage.

Input shaping is a technique that substantially reduces residual vibration based on the principle of destructive interference of impulse responses. Consider the cancellation of the two impulse responses in Fig. 2. If the impulse magnitudes

A_1 and A_2 and impulse time locations t_1 and t_2 are properly designed, the two impulse responses will cancel each other perfectly, resulting in zero residual vibration after the time t_2. Several methods can be used to find the impulse magnitudes and the impulse time locations. Original work by Smith [1] found them by obtaining the step response of the underdamped system in the so-called *Posicast* technique. Later work by Singer and Seering [5] found them by minimizing the so-called *percentage vibration*, which is the ratio of the residual vibration amplitude under an input shaper to the residual vibration amplitude of a unit impulse response without input shaper. Singh and Vadali [6] placed the zeros of the input shaping FIR filter at the flexible poles of the flexible systems. By doing so, they could obtain the impulse amplitudes and time locations, which are the design parameters in the FIR filter. Singhose et al. [7] obtained the input shaper by using a vector diagram. On the vector diagram, vectors representing the impulses are drawn so that their sum is equal to zero. Several researchers have designed the input shaper by using optimization problems. Normally, the impulse amplitudes and time locations were the optimization variables to be found. The input shaper length, which is equal to the time location of the last impulse, or the percentage vibration were used as a function to be minimized. One of the earliest work that used optimization problem is that of Pao and Singhose [8].

Manual control or human control of flexible systems, such as crane operator positioning a swinging payload, can be inefficient due to the residual vibration of the flexible parts. Besides, the task can be inaccurate and prone to accidental collision. Huey and Singhose [9] proposed the so-called *closed-loop signal shaping* (CLSS). In CLSS, the input shaper is placed inside the loop between the controller and the plant. An automatic controller is normally used in the system. Chatlatanagulchai et al. [10] showed that the time delay brought to the system by placing the input shaper inside the loop can deteriorate the performance of the controller by limiting the bandwidth of the closed-loop system. In manual control, where a human operator is used in place of the automatic controller, the time delay brought to the closed-loop system by the input shaper also affects the performance of the human operator in controlling the flexible systems.

Chatlatanagulchai et al. [11] proposed a novel technique, so-called *anti-delay closed-loop input shaper* (ACIS), to remove the effect of the time delay due to the input shaping from the closed-loop system. The Smith predictor was placed inside the loop to perform this task. The benefit of the proposed technique is that the human operator will not feel the delay because the delay is moved out of the loop, leading to more accuracy, shorter time, and less difficulty to complete the task. Besides, no modification is required on the input shaper.

In [11], the ACIS was applied to the manual control of a 3D crane model. Fig. 3 contains the diagram of the 3D crane with manual control via a joystick. Mathematical model was used to represent the 3D crane and its swinging payload. The model was programmed in a Matlab script. A joystick was connected to a USB port of the computer that runs the mathematical model. Several human operators performed that task of controlling the swinging payload via the joystick in an 8-point game, which is the game used in physical therapy. In this game, the payload must be placed at each point, which is selected randomly, within a specified accuracy before being allowed to move to the next point. Substantial improvements were observed from using ACIS over the CLSS and the without input shaping cases. Human operators were able to complete the 8-point game using less time and with low level of subjective difficulty, which is the difficulty the human operator feels when performing the task.

In this paper, the ACIS is implemented with an actual gantry crane hardware. A drawing of the gantry crane hardware is given in Fig. 4. There is a cart and a two-link pendulum. The cart has a motor, which is attached to the pinion gear. When the pinion gear is turned, the cart moves along the rack. There are three optical encoders to measure the cart position, the shoulder link's absolute angular position, and the elbow link's relative angular position. A payload is attached to the end of the elbow link. The shoulder joint and the elbow joint are very flexible and will oscillate when the cart is moved from point to point in order to position the payload.

Three techniques were implemented, and the experimental results were compared. The three techniques are the proposed anti-delay closed-loop input shaper (ACIS), the closed-loop signal shaping (CLSS) which is the currently best available technique, and without using the input shaper. Aspects that were compared include

- The time to finish the task in moving the payload from one point to another
- The accuracy in placing the payload at the desired position
- Subjective difficulty which is the difficulty level that the human operator feels when performing the task
- Performance improvement versus experience level of the human operator
- Amount of the oscillation of the payload
- Amount of electricity used to finish the task

A group of human operators performed the task in moving the payload from one point to another. Experimental results have shown that the proposed ACIS outperformed the CLSS and when the input shaper was not used.

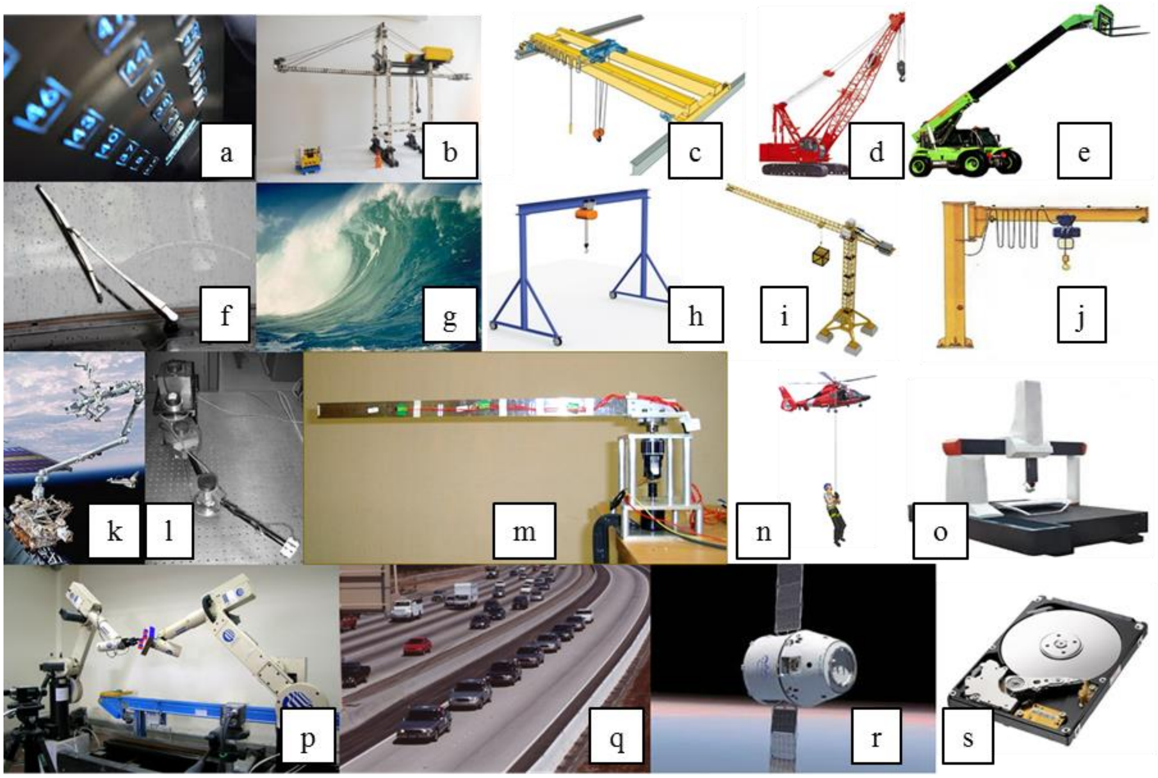

Fig. 1. Several flexible systems. a) Elevator. b) Quay-side crane. c) Bridge crane. d) Boom crane. e) Telescopic handler. f) Wiper. g) Wave dynamic. h) Gantry crane. i) Tower crane. j) Jib crane. k) Robot manipulator in space. l) Flexible-joint robot. m) Flexible-link robot. n) Helicopter with swinging payload. o) Coordinate measuring machine. p) Industrial robot. q) Car platoon. r) Spacecraft with flexible appendages. s) Hard disk read/write head with flexible gimbal. (Source: Ref. [1]).

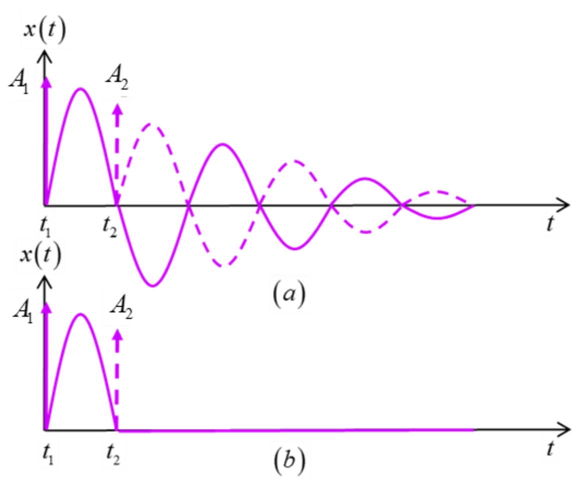

Fig. 2. Cancellation of two impulse responses. (Source: Ref. [1]).

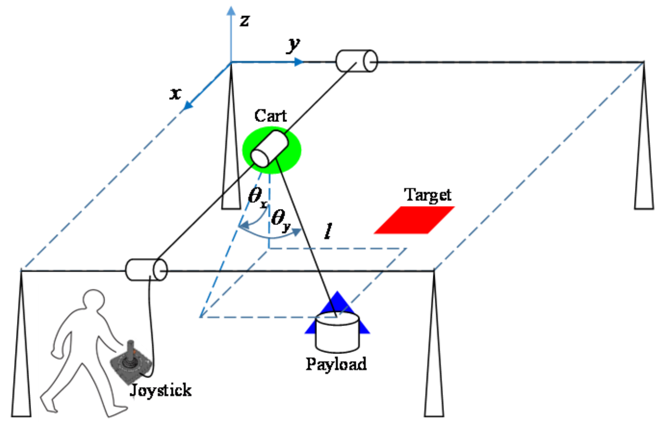

Fig. 3. Diagram of a 3D crane with manual control via a joystick. (Source: Ref. [11]).

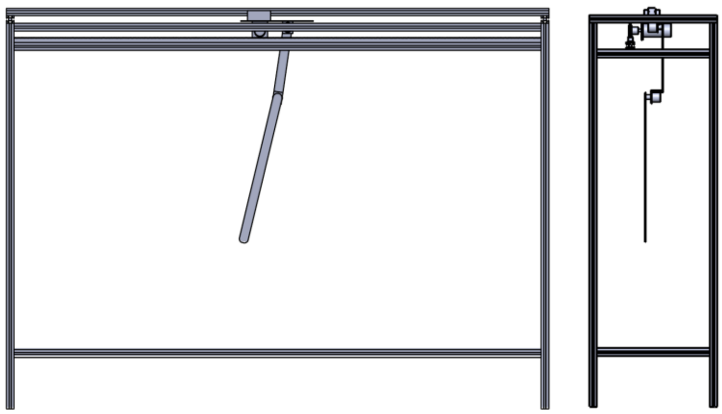

Fig. 4. Drawing of the gantry crane used in the experiment in this paper.

METHODOLOGY

A. Implementation of Input Shaping

The input shaper is normally implemented as an outside-of-the-loop FIR filter. Fig. 5 shows the implementation of this type; the so-called outside-the-loop input shaping (OLIS) [13], where r_b is the baseline reference signal, IS is the input shaping filter, r_s is the shaped reference signal, e is the tracking error, G is the feedback controller, u is the control effort, P is the flexible plant, and y is the controlled output.

The major advantage of the OLIS is that the time delay from the input shaping filter is outside the feedback loop; therefore, the time delay does not adversely affect the performance of the feedback system by limiting the controller bandwidth. However, in most cases, OLIS is not suitable for manual control, where a human operator is the feedback controller, G. This is because, in an industrial crane, for example, the command given by the human operator via the pendant is the control input, u, instead of the baseline reference signal, r_b.

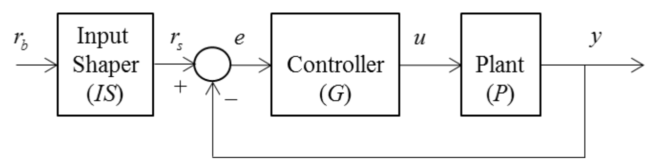

Fig. 5. Outside-the-loop input shaping.

In manual control, the control input, u, given by the human operator, must be shaped by an input shaper before sending to the plant, P, to avoid oscillation. This leads to an implementation scheme called closed-loop signal shaping (CLSS) [14]. The block diagram of CLSS is shown in Fig. 6.

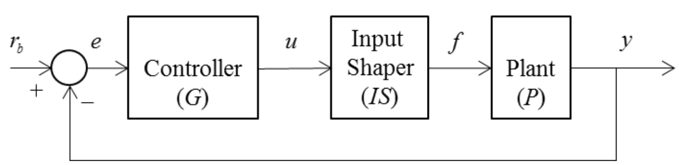

Fig. 6. Closed-loop signal shaping.

B. Anti-Delay Closed-Loop Input Shaping

Anti-delay closed-loop input shaping (ACIS) was proposed by the authors in [10] and [15]. Its block diagram is given in Fig. 7, where *C* is the feedback controller, *IS* is the input shaping filter, *P* is the flexible plant, *SM* is the Smith predictor, x_1 is the rigid output, x_2 is the flexible output, *r* is the reference for the rigid output, *u* is the control effort, *f* is the output from the input shaper, and *v* is the output from the Smith predictor. The Smith predictor has a transfer function,

$$SM(s) = \hat{P}(s) - \hat{P}(s)IS(s), \quad (1)$$

where $\hat{P}$ is the mathematical model of the actual plant, *P*.

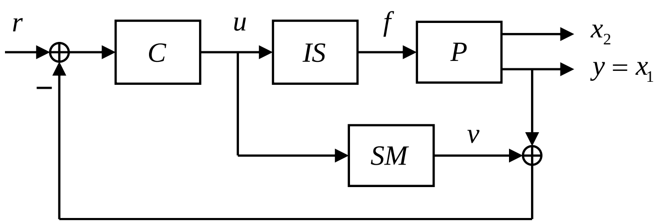

Fig. 7. Anti-delay closed-loop input shaping for the flexible system.

If the plant model is perfect, that is, $P = \hat{P}$, the transfer function from *r* to *y* can be computed as

$$\frac{y(s)}{r(s)} = \frac{C(s)IS(s)P(s)}{1 + C(s)P(s)},$$

which means the effect of the input shaper, *IS*, is removed from the loop.

C. Two-Link Pendulum on Gantry Crane

The anti-delay closed-loop input shaping technique, along with other comparable techniques, were trialed on a two-link pendulum on gantry crane, whose drawing is shown in Fig. 4.

Applying the Newton's law gives an equation of motion,

$$f - c\dot{x} = \left[m + \sum_{i=1}^{2}(m_i)\right]\ddot{x} - \Delta f, \quad (2)$$

$$\Delta f = -m_1\ddot{\theta}_1\frac{l_1}{2} - m_2\left(\ddot{\theta}_1 l_1 + \ddot{\theta}_2\frac{l_2}{2}\right),$$

where f is the push force to the cart, c is the damping constant, x is the absolute coordinate of the cart, m is the mass of the cart, m_i, $i = 1, 2,$ are the masses of link1 and link2, θ_i, $i = 1, 2,$ are the absolute and relative angular positions of link1 and link2, and l_i, $i = 1, 2,$ are the lengths of link1 and link2.

Δf can be viewed as a plant-input disturbance due to the inertia forces of the links. Around the operating points, the push force, f, is directly proportional to the command voltage, u, given to the cart motor by the human operator, that is,

$$f = ku, \quad (3)$$

where k is a constant.

From (2) and (3), neglecting the disturbance, Δf, the transfer function from the command voltage, u, to the cart position, x, is then given by

$$\frac{x(s)}{u(s)} = \hat{P}(s) = \frac{k}{\left[m + \sum_{i=1}^{2}(m_i)\right]s^2 + cs}.$$

Closed-loop system identification was performed on the gantry crane carrying two-link pendulum in Fig. 4. The cart was commanded to follow a frequency-varying sine wave. The resulting plant model, $\hat{P}(s)$, was obtained as

$$\hat{P}(s) = \frac{2.546}{0.326s^2 + s}. \quad (4)$$

This plant model will be used in the design of the manual control of the two-link pendulum on gantry crane.

D. Manual Control of the Two-Link Pendulum on Gantry Crane

Three configurations will be compared. First is the without-input shaper case. The diagram of the without-input shaper case is similar to that of Fig. 6, but the feedback controller is a human operator and there is no input shaper in the loop. The human operator watches the position of the cart, which is the plant output, *y*, and tries to command the cart via a joystick to follow the reference, r_b, closely.

Second is the closed-loop signal shaping (CLSS) case. The diagram of CLSS is shown in Fig. 6 when the feedback controller is a human operator and the input shaper is of the zero-vibration-and-k$^{\text{th}}$-order-derivatives (ZVD^k) type [5]. The gantry crane with two-link pendulum has two flexible modes. From using the logarithmic decrement method, the mode parameters of the two flexible modes were identified as $(\omega_1, \zeta_1) = (4.3\text{ rad/s}, 0.001)$ and $(\omega_2, \zeta_2) = (9\text{ rad/s}, 0.005)$, where ω_i is the natural frequency and ζ is the damping ratio. The ZVD^k input shaper has a general formula as [12]

$$A_i = \frac{\binom{k+1}{i-1}K^{i-1}}{\sum_{j=0}^{k+1}\binom{k+1}{j}K^j}, \; t_i = (i-1)\frac{\pi}{\omega_n\sqrt{1-\zeta^2}}, \; i = 1, 2, ..., k+2.$$

where $k = 0, 1, 2, ...,$

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

The ZVD^k input shaper has the total of $k+2$ impulses in the sequence. A_i is the normalized impulse amplitudes. t_i is the impulse timings.

$$\binom{n}{r} = \frac{n!}{r!(n-r)!}$$

is the combination of n things taken r at a time. The ZVD^k input shaping filter is then given by

$$\text{IS} = \prod_{j=1}^{n-1}\text{IS}(j), \; \text{IS}(j) = \sum_{i=1}^{k+2}A_i e^{-t_i s}, \quad (5)$$

where $\mathrm{IS}(j)$ is the ZVD^k input shaper for the j^{th} mode. In all the experiments to follow, k was set equal to two.

Third is the anti-delay closed-loop input shaping (ACIS). The diagram of ACIS is shown in Fig. 7. The Smith predictor is given by (1) with the plant model (4) and the input shaper (5). Fig. 8 shows the user interface during the experiment. The red dot is the desired position (r signal in Fig. 7). The blue dot is the actual position of the cart and the two-link pendulum as computed from the signals from the three optical encoders. The green dot is the feedback position ($v+x_1$ signal in Fig. 7). The human operator uses the joystick to make the green dot (the feedback signal) follow the red dot as closely as possible.

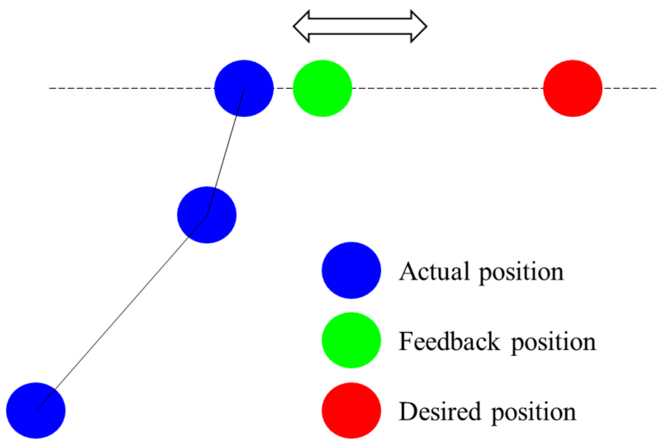

Fig. 8. User interface during the experiment.

RESULTS AND DISCUSSION

Fig. 9 shows the experiment with the gantry crane. Fig. 9(a) is when the input shaping was not used. The human operator watches the actual position of the cart in the monitor (the blue dot). His hand is on the joystick, which sends command to the motor driver board. The joystick movement is directly proportional to the amount of the force sending to the cart. The operator's goal is to control the payload position to follow the desired position (the red dot) as closely as possible. As can be seen in Fig. 9(a), without the input shaper, there is no time delay between the command from the operator and the movement of the cart, so the operator can control the cart conveniently. However, the swift movement of the cart excites the flexible modes of the pendulum, and the pendulum swings violently. As a result, the operator cannot place the payload at the desired position effectively because of the payload oscillation.

Fig. 9(b) shows the case when CLSS in Fig. 6 was implemented. The operator again watches the actual position of the cart in the monitor (the blue dot) and tries to make it follow the desired position (the red dot). Basically, the operator stops giving the joystick command when he sees that the actual position of the cart (the blue dot) has already reached the desired position (the red dot). However, because the input shaper (in Fig. 6) changes the command, u, given by the operator, to the plant control input, f, which contains time-delayed steps from the input shaper, the cart position (the blue dot) overshoots its desired position (the red dot). The overshoot of the cart results in the cart hitting the end stopper severely causing possible damage and the pendulum to swing severely. To avoid this, the operator needs to anticipate the stopping position of the actual cart position and must stop giving the command earlier. This results in the inaccuracy and subjective difficulty felt by the operator.

Fig. 9(c) contains the case when ACIS in Fig. 7 was used. The operator, this time, watches the feedback position signal (the green dot) and tries to make it follow the desired position (the red dot). The operator stops giving the command, u, because he sees that the feedback signal (the green dot) is already at the desired position (the red dot). Because the actual cart position (the blue dot) follows the feedback signal (the green dot) by the delayed time of the input shaper, the time-delayed steps in the plant control input, f, drives the actual cart position to the desired position without overshoot. The operator can then complete the task in placing the payload at the desired position using shorter time, with more accuracy, and with less subjective difficulty.

The three cases in Fig. 9 were compared. The experimental results are shown in Fig. 10. The desired position (the red dot) was randomly given to the operator. The operator must complete the tracking of ten desired positions. To move to the next desired position, the payload must be positioned within the window of $\pm 10\,\mathrm{cm}$ from the desired position and must stay within this window for three seconds. Ten human operators participated in the experiment. Each of them was trained for ten minutes to be familiar with the control of the payload. Then, each operator was asked to perform the three cases, once per case.

TABLE I. SUBJECTIVE DIFFICULTY RATING SCALE

Rating	Description
1-3	Desired performance attainable with zero (1) to minimal (3) mental effort/compensation
4-6	Desired performance requires moderate (4) to intense (6) mental effort/compensation
7-9	Desired performance not met; Maintaining control requires mild (7) to intense (9) effort
10	Control cannot be maintained

Fig. 10(a) shows the average time to finish. Fig. 10(b) contains the accuracy level of placing the payload at the desired position. The accuracy level is measured from the absolute distance between the cart position and the desired position when the payload stays within the window. Fig. 10(c) presents the subjective difficulty level based on the Cooper-Harper rating scale, presented in [16]. The rating scale is shown in Table 1, which is taken directly from [16]. Fig. 10(d) shows the amount of oscillation of the pendulum throughout the movement. The amount of oscillation is the root-mean-square value of the payload angle.

It can be seen from Fig. 10 that the ACIS has the shortest time to finish, the best accuracy, the least subjective difficulty, and the least amount of oscillation.

CONCLUSIONS

A recently proposed technique for manual control of flexible systems was implemented and evaluated on a gantry crane carrying a two-link pendulum. This anti-delay closed-loop input shaping (ACIS) technique makes use of the Smith predictor in removing the time delay due to the input shaper from the feedback loop. Experimental results show that ACIS outperforms the conventional manual control techniques in terms of time to finish, accuracy in placing the payload, subjective difficulty, and amount of oscillation.

However, there are two disadvantages of ACIS. First, it requires accurate rigid-body plant model. Inaccurate plant can deteriorate the performance of the Smith predictor in removing the time delay from the feedback loop, resulting in lower performance of ACIS. Nevertheless, accurate rigid-body plant model is usually relatively easy to obtain. Second, the human operator must watch the feedback position on a monitor. The feedback position is computed from the actual cart position. Therefore, one monitor and actual cart position are required to implement ACIS in any flexible systems.

Future work is to evaluate the outside-the-loop input shaping, whose diagram is given in Fig. 5, for manual tracking of flexible systems. By placing the input shaper outside the loop, its time delay has no effect to the system. The operator can watch the shaped reference signal and try to command the rigid output to follow it.

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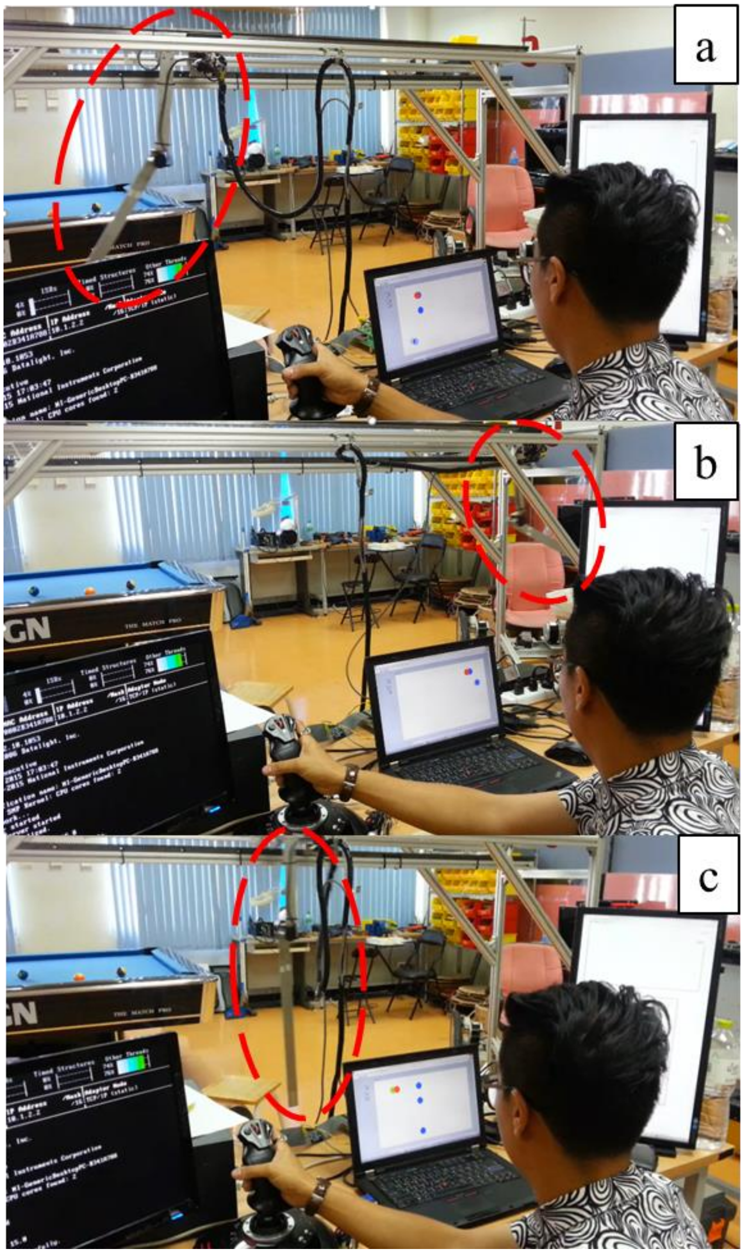

Fig. 9. Experiment with the gantry crane. (a) Without input shaping. (b) CLSS. (c) ACIS.

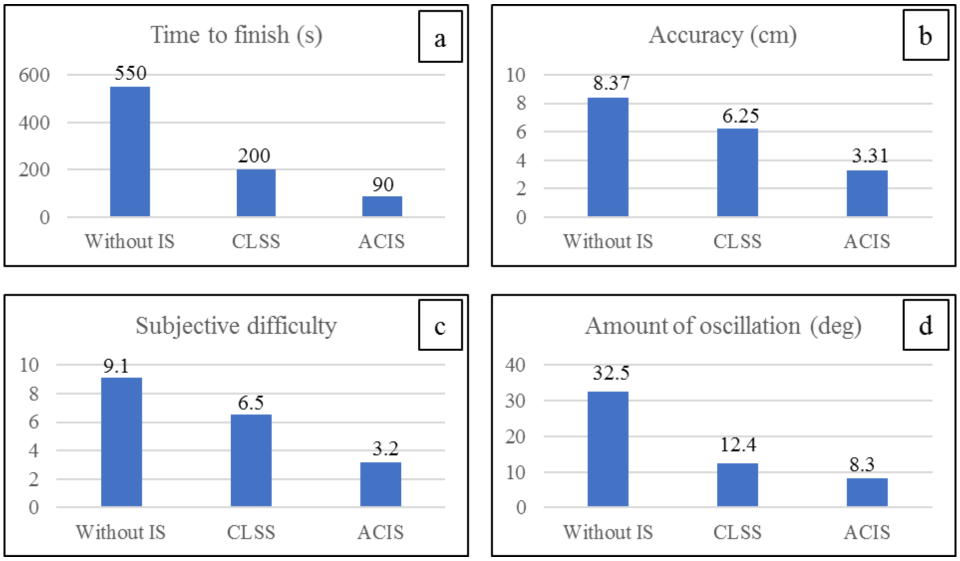

Fig. 10. Comparison results. (a) Time to finish. (b) Accuracy. (c) Subjective difficulty. (d) Amount of oscillation.