Novel Virtual Training System to Learn the Sway Suppression of Rotary Crane by Presenting Ideal Operation of Joystick or Visual Information

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Abstract: In this paper, we propose a novel virtual training system capable of shortening the training period of unskilled crane operators. First, a simulator representing the motion behavior of load and boom during transfer operation in crane's cockpit is newly built. Second, referring to such the sway suppression skill taught in crane driving school, sway suppression control input is theoretically derived. Thirdly, a learning support method with ideal operation of joystick or visual sensory information to facilitate acquisition of the sway-suppression skill for unskilled operators is proposed. Finally, a lot of experiments were performed to validate the effectiveness of the proposed learning support method.

1 INTRODUCTION

Rotary cranes are widely use c d at factories, harbors, and construction sites to load and unload cargo. Figure 1 shows a rotary crane. A rotary crane performs boom rotation, boom hoisting and load hoisting. Owing to its simple structure, a rotary crane can be easily disassembled, transported, and reassembled. Another big advantage of a rotary crane is that the very large workspace is achieved with a relatively small footprint.

However, owing to acceleration or deceleration and centrifugal force, load sway is often generated during transport operations. When load sway is generated, it brings the problems on the accuracy of load to target position, work efficiency and safety. To solve these problems, it becomes important for crane operators to acquire sway suppression skill, and furthermore, acquisition of the skill in short training period is also needed.

In regard to how this skill is acquired, training methods are frequently employed in which actual crane are used, but such methods involve a risk of accidents during the training period. In view of the safety hazard, various virtual crane simulators have been developed that enable training to be conducted without the training of actual cranes. In J.Y Huang et al., the development of the training simulator with high realistic sensation where the beginner operator

Figure 1: A rotary crane in the construction site.

could learn the skill of crane operation beforehand is attracting much attention (Jiung et al., 2003). In M.F.Daqaq et al., a virtual simulation of a ship-mounted crane is carried out in Cave Automated Virtual Environment (CAVE) (Mohammed et al., 2003). A six degrees of freedom motion base was used to simulate the motion of a ship. The simulation serves as a platform for studying the dynamics of ships and ship-mounted cranes under dynamic sea environments, and also as a training platform for operators of ship-mounted cranes. Although those simulators perform well in terms of realistic sensation, the training function is insufficient. Thus, unskilled operators have to acquire the sway suppression skill by trial and error. As a result, a long period of training is needed to acquire the sway suppression skill. Terashima's group researches about shipboard crane training simulator for beginners (Iwasa et al., 2010; Young Jian et al., 2011). However, these basic studies are

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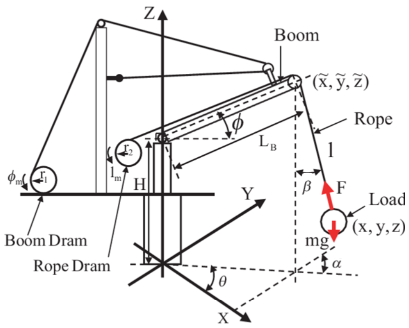


Figure 2: Schematic of rotary crane for a load position model.

unmatched with the actual cockpit view of a crane, because the simulator is built as the operator view position fixed around a crane. In addition to this fact, the interface of the training system was only the one with the presence of ideal operation of joystick information, and therefore the comparison and consideration of interface with the presence of other information were highly demanded.

The purpose of the present study is to develop a simulator capable of shortening the training period for unskilled crane operators for rotary cranes. First, we create a virtual crane simulator using a rotary crane model. Display on crane of simulator is given by viewing from the cockpit which is rotated by crane, while the display on crane of simulator in the author's former researches (Iwasa et al., 2010; Young Jian et al., 2011) was given by the fixed cockpit such that cockpit was set on the ground. Next, sway suppression control input is derived theoretically. Thirdly, using this control input, we propose novel two learning support methods that present ideal operation of joystick or visual sensory information to facilitate acquisition of the sway suppression skill for unskilled operators. For the former presentation of ideal operation of joystick information, control input with anti-sway against centrifuged force is reproduced by using an active joystick. Active Joystick is automatically moved by using the inverse kinematics of joystick's motor model, and operators can naturally learn the ideal operation by holding joystick. On the other hand, for the latter presentation of visual information, control input is shown by an indicator on computer display. Unskilled crane operators are able to acquire the sway suppression skill by spontaneously operating the joystick following to the visual guidance from the indicator. The usefulness of the proposed method is demonstrated through various simulation experiments.

2 DYNAMICS OF ROTARY CRANE

The motion of rotary crane is different from the linear motion of an overhead crane or a gantry crane. In the case of a rotary crane, the motion of the load has an arc-like trajectory, and considering the effect of centrifugal force, it is necessary to model the load sway as a circular cone pendulum. A diagrammatic illustration of a rotary crane is shown in Figure 2. In addition, the system is simplified by the following assumption.

A crane is a rigid body and, considering the load is a mass point, the rope's weight, deflection and elasticity are ignored. The friction and backlash for the power transmission device are ignored. Boom tip position and load position are represented by Equations (1) and (2). The equation of swing angle of a load is represented by Equations (3) and (4) (see Shen et al., 2003).

Model of Boom tip trajectory:

$$\begin{aligned}\tilde{x} &= L_B\cos\theta\cos\phi,\\ \tilde{y} &= L_B\sin\theta\cos\phi,\\ \tilde{z} &= H + L_B\sin\phi.\end{aligned} \tag{1}$$

Model of load position:

$$\begin{aligned}x &= \tilde{x} + l\sin\alpha,\\ y &= -\tilde{y} - l\cos\alpha\sin\beta,\\ z &= \tilde{z} - l\cos\alpha\cos\beta.\end{aligned} \tag{2}$$

Model of swing angle of load:

$$\begin{aligned}&\ddot{\alpha}l(\cos\alpha + \sin\alpha\ \tan\alpha) + \ddot{\beta}l\sin\alpha\tan\beta + \dot{\beta}^2 l\sin\alpha\\ &- 2\dot{\alpha}\dot{\beta}l\sin\alpha\tan\alpha\tan\beta + g\sec\beta\tan\alpha\\ &= -\ddot{\theta}l\cos\alpha\sin\beta + \dot{\theta}^2(L_B + l\sin\alpha)\\ &+ 2\dot{\theta}l(\dot{\alpha}\sin\alpha\sin\beta - \dot{\beta}\cos\alpha\cos\beta),\end{aligned} \tag{3}$$

$$\begin{aligned}&\ddot{\beta}l(\cos\alpha\cos\beta + \sin\beta\cos\alpha\tan\beta)\\ &- \dot{\alpha}\dot{\beta}(\cos\beta\sin\alpha + \sin\beta\cos\alpha\tan\beta) + g\tan\beta\\ &= \ddot{\theta}(L_B + l\sin\alpha) + \dot{\theta}^2 l\cos\alpha\sin\beta + 2\dot{\theta}\dot{\alpha}l\cos\alpha.\end{aligned} \tag{4}$$

where $\tilde{x},\tilde{y},\tilde{z}$ [m] is three-dimensional coordinate of Boom tip position, [m] is three-dimensional coordinate of load position, L_B [m] is length of Boom, θ [rad] is rotary angle, φ [rad] is Boom angle, l [m] is length of rope, α [rad] is sway angle of radius direction, and β [rad] is sway angle of slew direction.

3 CONSTRUCTION OF VIRTUAL SIMULATOR

In this section, a virtual crane simulator using crane model is built. The present visual simulator consists of displayed graphics of crane boom and load, and joystick displayed graphics for operation. The graphics on computer display is created using Open GL. Operational view of this simulator configures from a cockpit of a crane, and translates its view position with slew motion of crane cockpit. Operational interface (device) for virtual simulator uses Active Joystick (will be explained later). Flow of this simulator is shown in Figure 3. First, read velocity input from Active Joystick. Second, it calculates operational amounts of rotary, Boom hoisting, and load hoisting from velocity input. Thirdly, it calculates the states of Boom tip and load using crane model. Finally, it makes a static graphic of a crane, and renders its graphics at 30 [msec] intervals. By repeating this flow, it is displayed crane graphic naturally on real-time. Figure 4 shows virtual crane simulator built with Active Joystick.

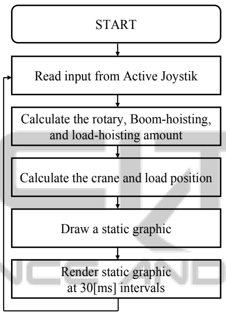


Figure 3: Flow of simulator.

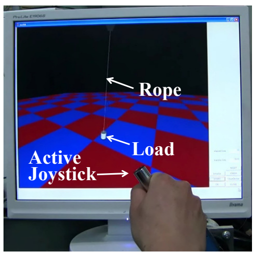


Figure 4: Visual crane simulator.

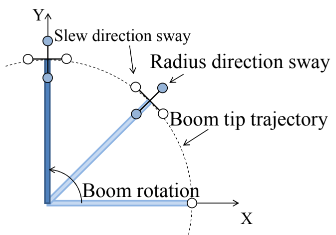


Figure 5: Characteristics of load sway for a rotary crane.

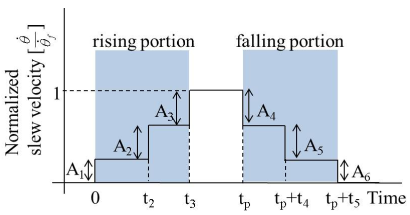


Figure 6: 2-Mode Input Shaping command template.

4 DERIVATION OF SWAY SUPPRESSION CONTROL INPUT

The load sway of a rotary crane is affected by acceleration or deceleration of the boom and centrifugal force, because the boom is rotated. Thus, load sway becomes two-dimensional sway consisting of radius direction sway and slew direction sway (see Figure 5). Additionally, in the case that the boom rotates 90 degrees, the slew direction sway mutates into the radius direction sway from initial position to target position in absolute coordinates.

Given these facts, we use the 2-Mode Input Shaping method by Shighose et al. (Jason et al., 2010), in which velocity variation changes in three steps for the anti-sway. Because the Input shaping control method is very intuitive one, it is considered that it is easier for operators to train the anti-sway control input compared with other methods (see Figure 6). The optimal velocity A_i [rad/s] and the timing of velocity variation t_i [s] are derived to minimize residual sway. This method can control the residual radius direction sway and slew direction sway by only rotary actuator. Time t_p [s] is the arbitrary time at which the crane is commanded to begin decelerating. The vertical axis is normalized by the final setpoint slew velocity $\dot{\theta}_f$ [rad/s] yielding

$$A_1 + A_2 + A_3 = 1 \tag{5}$$

$$A_4 + A_5 + A_6 = -1 \tag{6}$$

This means that only amplitudes A_1, A_2, A_4, and A_5 need to be derived since A_3 and A_6 can be found directly from Equation (5) and (6).

The relational expression of slew velocity and sway angle becomes Equation (7).

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\beta} \\ \dot{\alpha} \\ \ddot{\alpha} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 1 \\ \left(\dot{\theta}^2 - \omega_0^2\right) & 0 & 0 & 2\dot{\theta} \\ 0 & 0 & 0 & 1 \\ 0 & -2\dot{\theta} & \left(\dot{\theta}^2 - \omega_0^2\right) & 0 \end{bmatrix} \begin{bmatrix} \beta \\ \dot{\beta} \\ \alpha \\ \dot{\alpha} \end{bmatrix} \quad (7)$$

Here, α and β have high-frequency modes and low-frequency modes respectively from characteristic value of state equation. Here, the sum of high-frequency modes defines v_{jk} [rad], and the sum of low-frequency modes defines y_{jk} [rad], ω_0 [rad/s] is natural frequency. These modes can be expressed by Equation (8) and (9):

$$v_{jk} = -\frac{L_B}{2l\omega_0}\left(\frac{\dot{\theta}_k\omega_0}{\omega_k^+} + \dot{\theta}_j\left(-1 + \frac{\dot{\theta}_j\omega_k^-}{\omega_j^+\omega_j^-}\right)\right) \quad (8)$$

$$y_{jk} = \frac{L_B}{2l\omega_0}\left(\frac{\dot{\theta}_k\omega_0}{\omega_k^-} - \dot{\theta}_j\left(1 + \frac{\dot{\theta}_j\omega_k^+}{\omega_j^+\omega_j^-}\right)\right) \quad (9)$$

where,

$$\omega_j^+ = \omega_0 + \dot{\theta}_j, \qquad \omega_k^+ = \omega_0 + \dot{\theta}_k,$$
$$\omega_j^- = \omega_0 - \dot{\theta}_j, \qquad \omega_k^- = \omega_0 - \dot{\theta}_k$$

Here L_B =17.5[ml], l = 20[m], $\dot{\theta}_j$ is slew velocity before input A_i, $\dot{\theta}_j$ is slew velocity before input A_i, ω_j^+ [rad/s] and ω_j^- [rad/s] are the high and low modes at $\dot{\theta}_f$ respectively, while ω_k^+ [rad/s] and ω_k^- [rad/s] are the high and low modes at $\dot{\theta}_k$, respectively. By recursively applying Equation (8) and (9) to the command template in Figure 6, the complex valued residual sway of two modes, v_{tot} [rad] and y_{tot} [rad] can be derived as follow:

$$v_{tot} = v_{01}e^{i\left(\omega_1^+ t_2 + \omega_2^+ (t_3 - t_2)\right)} + v_{12}e^{i\omega_2^+ (t_3 - t_2)} + v_{23} \quad (10)$$

$$y_{tot} = y_{01}e^{i\left(\omega_1^+ t_2 + \omega_2^+ (t_3 - t_2)\right)} + y_{12}e^{i\omega_2^+ (t_3 - t_2)} + y_{23} \quad (11)$$

Where v_{tot} and y_{tot} are found from Eps. (8) and (9) (Equation (5) - (11) details; see the original papers of Singhose, et al. (David, 2002).) These terms are the change in the complex amplitudes of first and second caused by a step transition from $\dot{\theta}_f$ to $\dot{\theta}_k$,

$$\dot{\theta}_0 = 0, \quad \dot{\theta}_1 = \dot{\theta}_f A_1, \ \dot{\theta}_2 = \dot{\theta}_f\left(A_1 + A_2\right), \dot{\theta}_3 = \dot{\theta}_f \quad (12)$$

where A_1, A_2, t_2, and t_3 refer to the step amplitudes and times shown in Figure 6.

In rising portion (acceleration interval), it needs to derive A_1, A_2, t_2, and t_3 such that v_{tot} and y_{tot} are minimized. Similarly, it needs to derive A_4, A_5, t_4, and t_5 in falling portion (deceleration interval). This study minimizes using conjugate gradient method, and run a simulation. By simulation result in Figure 7, it was able to confirm that 2-Mode Input Shaping reduce residual sway of the load. And that, the timing of changing velocity in second step and third step was turn out when the sway angle and a crane become vertical.

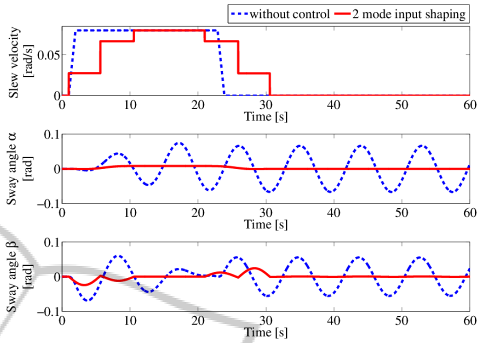


Figure 7: Simulation result for 2-Mode Input Shaping.

5 PROPOSED LEARNING ASSIST SYSTEM

Instructors verbally explain the sway suppression techniques at the crane driving school. Beginners receive the explanation, and then practice crane operation by themselves. However, this training method will be not the sufficient training for beginners. In this section, using the 2-Mode Input Shaping method described in the previous section, a novel training system for beginners that teaches the amount and timing of acceleration or deceleration is presented. By teaching these operational skills, we hope that the training effect will be enhanced and the training period shortened for beginners. So, we propose the training system by giving sensory information of humans such as ideal operation of joystick or visual information. In this paper, two methods of teaching operational skills are proposed. One is ideal operation of joystick guidance training by presenting ideal operation of joystick information, and the other is visual guidance training by presenting visual information.

One training method we propose is often used in sports training and skills education. Such training through hands-on coaching is known to be effective in many situations. This study focused attention on this point, and proposes ideal operation of joystick guidance training by the joystick of operational interface for obtaining the sway suppression skill. Principle of this learning method is as follows. Namely, active joystick interface is automatically moved by using inverse kinematics of motor model from anti-sway reference velocity obtained from 2-Mode Input Shaping method. Then, beginners are able to learn a sense of the skill by touching its joystick with his or her hand and feeling the motion.

Figure 8 shows the Active Joystick that is the operational interface used in this study. This joystick is equipped with a 6-axis force sensor and AC servo motors. The joystick rotates on the X_J-axis and Y_J-axis. If the joystick is tilted on X_J-axis, it rotates the rotary crane, and if it is tilted on Y_J-axis, the boom is hoisted. In order to drive the joystick, 2 AC servo motors with harmonic drive (speed reduction ratio = 1:100) are utilized. A force/torque sensor is attached on the joystick to measure the force that the operator applies to the joystick.

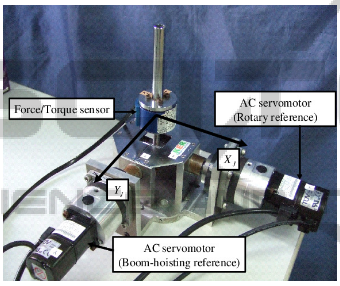


Figure 8: Active Joystick.

Furthermore, the joystick incorporates a spring mass damper model so that an operator can move the joystick using relatively little force and when the operator removes his hand from the joystick, the joystick automatically returns to its starting point. The joystick's motion equation is expressed as follows:

$$J_r\ddot{\theta}_J + d_r\dot{\theta}_J + k_r\theta_J = M_y \tag{13}$$

where, θ_J : joystick's inclination angle from original point, M_y: force applied on joystick by operator, J_r = 0.1[kgm^2]: inertia moment, d_r = 0.7 [Nms/rad]: viscous friction coefficient, and k_r = 1.65 [N/m]: spring constant.

Figure 9 shows outline of learning assist system. This system converts the sway suppression control input into driving voltage of motors, and replicates its input by its joystick. Beginners can learn to the sway suppression skill sensuously, because they feel maneuvering feeling like getting coaching from expert. Thus, they will be able to achieve its

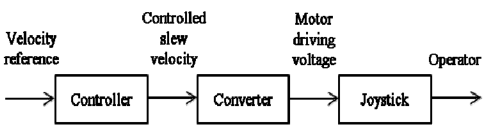


Figure 9: Diagram of haptic guidance.

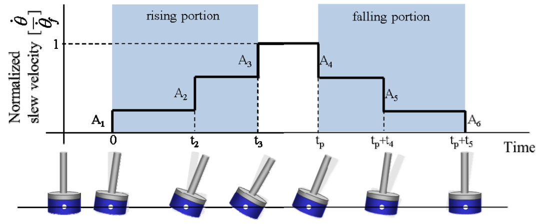


Figure 10: Motion of Active Joystick for each time.

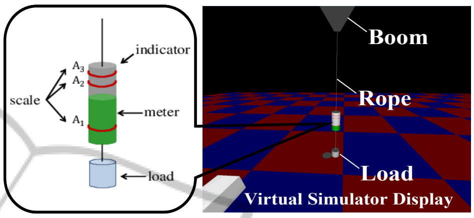


Figure 11: Indicator for visual guidance.

operational amount and the timing by using this training (see Figure 10).

The other training method that we propose is visual guidance training involving the presentation of visual information. An indicator is displayed on the screen of the crane simulator shown in Figure 11. This indicator shows the amount of acceleration or deceleration A_i on a three-step scale for control of the load sway. The height of the meter changes in proportion to joystick angle. Thus, beginners will be able to learn the amount and timing of acceleration or deceleration required by spontaneously manipulating the joystick in accordance with the scale.

6 RESULTS OF VIRTUAL TRAINING EXPERIMENTS AND DISCUSSION

The effectiveness of the proposed novel learning assist system was evaluated by means of an experiment. In this experiment, training was conducted for 13 men who had no experience of crane operation. The subjects were divided into the following four groups:

- Group A: 2 men, self-training, without oral presentation
- Group B: 3 men, self-training, with oral presentation
- Group C: 4 men, ideal operation guidance training
- Group D: 4 men, visual guidance training.

Before starting the experiment, the sway suppression skill was explained verbally to each group, excluding Group A. Using the crane simulator that we developed, each group transports a load (height:0.9[m], radius:0.3[m]) several times. Each group transports the load to a circular target position (radius: 0.4[m]) by turning the rotary crane 100[deg]. For automatic transportation using 2-Mode Input Shaping, transfer time is 29.6[s]. However, for transportation by manual operation, it is almost certain that human error will occur. Thus, in consideration of human error, transfer time is set to within 35.0[s]. Parameters of the rotary crane simulator are listed in Table 1, and parameters of 2-Mode Input Shaping shown in Table 2.

Table 1 : Parameter of rotary crane for training use.

Parameter	Symbol	Value	Units
Rope length	l	20.0	m
Boom length	L_B	17.5	m
Boom hoisting angle	ϕ	45.0	deg
Max slew velocity	θ	0.08	rad/s

Table 2: Parameters of 2-Mode Input Shaping.

A_1	A_2	t_2	t_3
0.3442	0.4902	4.6476	9.5657
A_4	A_5	t_4	t_5
0.1673	0.4912	4.9161	9.5701

The training schedule is shown in Figure 12. First, subjects of each group transport the load three times without assistance, and then they transport the load three times with assistance. This flow is treated as one set, and this set is conducted five times. Finally, one set is conducted again without assistance, and residual sway of all test sets is evaluated. Training time of one set is about 3 minutes, all training time is about 40 minutes with break time.

The learning effect is evaluated on the basis of residual sway. Figure 13 shows the average residual sway angle for trials of each group. Figure 13 (a) shows that subjects in Group A were unsure about the crane operation because they were not given information about it. Figure 13 (b) shows that the average residual sway angle for Group B was on a modest declining trend. However, because subjects in Group B were not informed of the amount and timing of acceleration or deceleration required, they had to ascertain it by trial and error. Therefore, the training effect for Group A and Group B was low. Figure 13(c) shows that the average residual sway angle for Group C steeply trended downward. As the subjects in Group C were able to experience the ideal sway suppression skill through ideal operation guidance, they were able to replicate it well. Therefore, we conclude that the ideal operation guidance training is effective. However, as shown in Figure 13 (d) Group D's results were superior to those of the other groups, which is considered to be attributable to the superior effect of visual guidance training because it allows the subjects to recognize the disparity between actual and ideal input and rectify it by spontaneous joystick operation in real time.

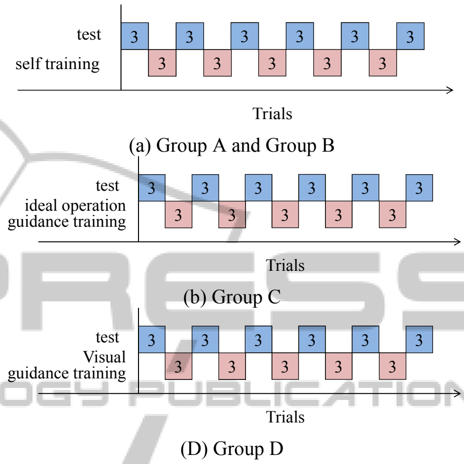


Figure 12: Training schedule for each group.

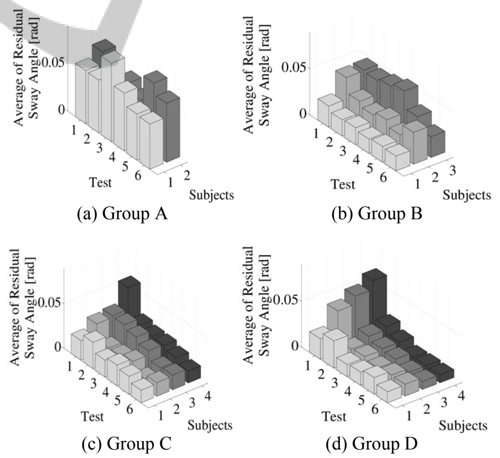


Figure 13: Training result for each group.

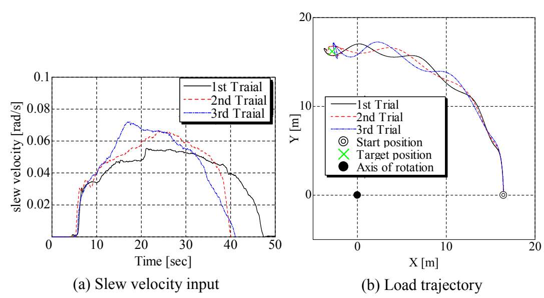
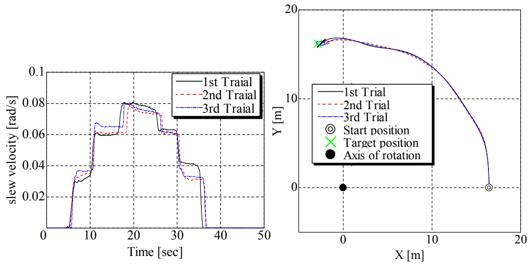
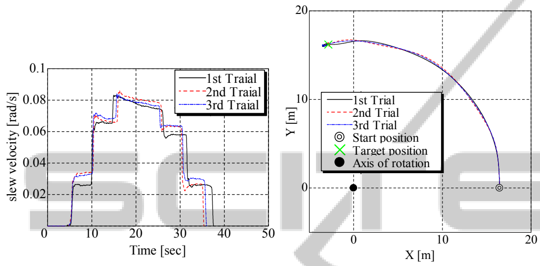


Figure 14: Training result of 6th test by certain subject in Gourp A.



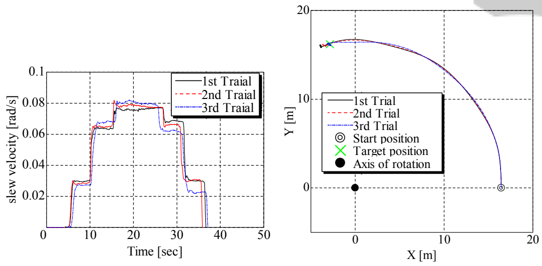
(a) Slew velocity input (b) Load trajectory

Figure 15: Training result of 6th test by certain subject in Gourp B.



(a) Slew velocity input (b) Load trajectory

Figure 16: Training result of 6th test by certain subject in Gourp C.



(a) Slew velocity input (b) Load trajectory

Figure 17: Training result of 6th test by certain subject in Gourp D.

Figure 14 through Figure 17 shows the slew velocity input and the load trajectory of the 6th test involving certain subjects of each group. Slew velocity of Group D is reproduced stably three times and load trajectory is comparatively smooth. Figure 18 shows the diminishing rate of residual sway by comparing the results of the first test with those of the final test. As can be seen from these results, the learning assist system will shorten the training period for beginner crane operators. In addition, the efficiency of work will increase because of a decrease in residual sway.

Furthermore, we conducted simulation experiments for various lope length such as l=15[m], 25[m] and l=30[m]. In any cases, we obtained the results of learning effects as almost same as the results of l=20[m] if we learn how to operate for anti-sway by using 2-Mode Input Shaping method for each order rope length. We omitted the results due to the limitation to validate the proposed method in real processes. We will show the results in the presentation of ICINCO 2013 conference. We can learn the skill for various rope length of l=20-100[m] so long as we learn how to operate for the rope length of l=20[m] and l=100[m] at both ends.

Now, an alternative method as training way will be discussed here. A way to present ideal movements of joystick proposed in this paper can certainly teach the motion of joystick, but not the force to push joystick. After learning how to move the joystick without force information, operator must operate joystick by grasping it. Then, operator needs not only motion, but also force reference information. Therefore, through the results of this study, a learning system is expected such that ideal force for anti-sway is memorized in computer, and a haptic feedback is worked against operator's actual force input. Furthermore, a hybrid training system constructed of haptic feedback and visual indicator proposed in this paper may be better. We will also present them in near future.

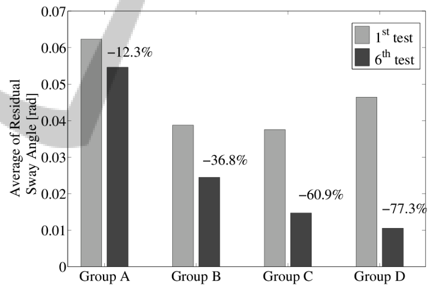


Figure 18: Comparasion of residual sway before and after training for each group.

7 CONCLUSIONS

In this study, we built a virtual crane training simulator such as presenting sway suppression skill. The results are as follows.

1. A crane training simulator using rotary crane model has been built.
2. As operational interface for simulator, Active Joystick presenting ideal operation of joystick information is developed.
3. The sway suppression control using 2-Mode Input Shaping method is applied in this study, and sway suppression is well achieved.
4. Guidance training methods by presenting ideal operational joystick or visual information are proposed.

5. It was clear that visual guidance training decreased 77% of residual sway than conventional training in the same training time through many simulation experiments.

As future work, we apply this result to real experimental apparatus. Furthermore, we plan to extend to shipboard crane with the present training function. The operation of shipboard crane is highly required to get operational skill, because crane operator must consider complicated ship sway in addition to anti-sway on boom and load of crane.

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