Development of Training Simulator for Sway Suppression Skills on Shipboard Rotary Cranes

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Abstract: In this paper, we develop the operational training system by teaching control input to crane operators. In particular, it is applied to the sway suppression control of load, by utilizing optimal control input. If crane operators can replicate its control input, they can operate crane suppressing the load sway, and hope the advance of training effect. Firstly, we build a shipboard rotary crane simulator, and verify the validity of the training simulator by transfer simulation. Nextly, it presents a sway suppression control method to obtain control input for crane operators, and proposes the training system to teach its control input to operators. Finally, the crane simulator integrates this training system, and the proposed training system verifies the validity by subjects experiments.

1 INTRODUCTION

A shipboard crane that is equipped on the ship is widely used for cargo work in harbors or construction sites. Many kinds of shipboard crane are such as small crane salvage barge that is several hundred tons; bucket dredger that is used for digging or removing mud and sand; and large non-sailing crane barge that is thousands of tons. Recently, shipboard crane have become larger for construction of pipeline, installation of caisson or offshore work in harbor or seacoast. Generally, large shipboard crane had no rotary function. However, rotary shipboard crane that is effective for work has also become larger recently. Large shipboard crane is required quick working, because you must pay out very expensive anchorage charges. So, it is required that the sway of the load is suppressed and you transport it quickly. However, these were depended heavily on the technique of skilled operator. Additionally on the shipboard, ship sway is also generated by wave and crane motion. Thus, operators must consider these matters and operation is very difficult. On the other hand, operation work of a crane is considered to be typical one of heavy, dirty and dangerous work. So, shortages of skilled operator have become serious problem. As solution of these problems, in this study, a training assist system for novice operator is proposed. The training using real machine has the risk of serious accident. In addition, acquisition of safety and quick transportation technique is required a certain level of experience. So, safety environment for operation training required. As alternative method of training using real crane, crane simulators have been actively developed(Jiung Yao Huang, 2003)(Mohammed F.Daqaq, 2003). If you use these simulators, you can safely and easily train without accident by the operating mistake. Currently, various realistic crane simulators that are reappeared real work environment have been developed(R.Ito, 2009)(K.Watanuki, 2007). However, many simulator cannot contribute to reduction of the training time, because try and error exercise are required. In this study, the training assist system that applies a human sense is developed. The purpose of our study is development of the simulator such that novice operator can efficiently master complex operation technique of the shipboard rotary crane. And we discuss construction of better control system.

2 THE SYSTEM CONSTRUCTION

This system is comprised of shipboard rotary crane training simulator and operating interface. Proposed shipboard crane simulator is used existing graphics library (OpenGL) of highly-portable. Active-joystick is employed as operating interface. Trainees operate shipboard crane on the simulator while seeing display

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monitor and using active joystick.

2.1 Graphics Library

3D graphics library of the simulator is using OpenGL. OpenGL have functions such as 3D display, control of the colors or pattern, geometric transform and shading compensation. So, OpenGL is a simple graphics free software. In addition, OpenGL can develop a system without dependence for operating system.

2.2 Interface for Operation - Active Joystick

Operating interface employs active-joystick developed in our laboratory (Fig.1). This active-joystick has 6-axis force sensor, and X and Y-axis AC servo motor. Firstly, force sensor feels operator's force. Second, AC servo motor is driven depending on operator's force. AC servo motor realizes smooth motion of the active-joystick, because of the compliance control.

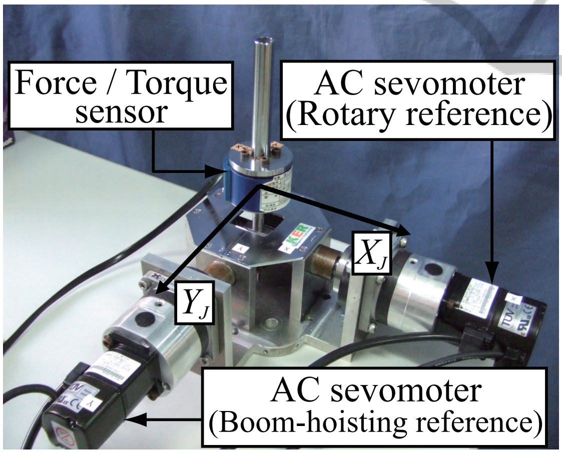


Figure 1: Experimental equipment of active joystick.

3 SHIPBOARD ROTARY CRANE MODEL

In this study, shipboard rotary crane model is constructed of both the rotary crane model and a brief ship model.

3.1 Rotary Crane Model

Schematic diagram of the target rotary crane is shown in Fig. 2 and its parameter is shown in Table 1. In order to simplify the system, the following assumption is summarized:

- A crane is a rigid body.
- 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 inored.

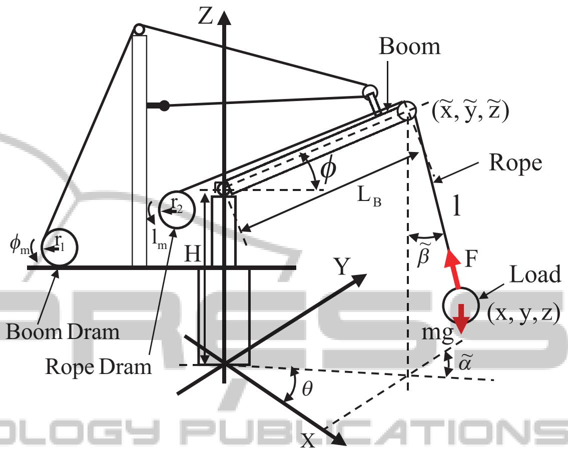


Figure 2: Schematic diagram of rotary crane for a load position model.

Table 1: Parameter of a load position model.

Symbol	Unit	Appellation
θ	rad	rotary angle
ϕ	rad	boom angle
l	m	length of the rope
L_B	m	length of the boom
H	m	height of the turn table
m_L	kg	mass of the suspended load
m_B	kg	mass of the boom
m_S	kg	mass of the ship
g	m/s^2	gravity
F	N	tension of the rope
v_W	m/s	wind velocity
$\tilde{\alpha}$	rad	swing angle on the horizontal surface
$\tilde{\beta}$	rad	swing angle from the vertical direction
α	rad	swing angle on the X-axis direction
β	rad	swing angle on the Y-axis direction
$(\tilde{x},\tilde{y},\tilde{z})$	m	position of the crane tip
(x,y,z)	m	position of the load
(v_{Wx},v_{Wy},v_{Wz})	m/s	wind velocity of each axis direction

The motion of a 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 Fig 2. In addition, the system is simplified by the following assumption. By seeing Fig.2, the boom tip position in the crane coordinate $(\tilde{x}', \tilde{y}', \tilde{z}')$ is calculated using

Eqs.(1)-(3) as follows:

$$\tilde{x}' = L_B \cos\phi \cos\theta \quad (1)$$
$$\tilde{y}' = L_B \cos\phi \sin\theta \quad (2)$$
$$\tilde{z}' = H + L_B \sin\phi \quad (3)$$

Coordination transformation from Σ' to Σ is done using Eq.(4).

$$\tilde{X} = T_{xyz}\tilde{X}' \quad (4)$$
$$\frac{d\tilde{X}}{dt} = \frac{dT_{xyz}}{dt}\tilde{X} + T_{xyz}\frac{d\tilde{X}'}{dt} \quad (5)$$
$$\frac{d^2\tilde{X}}{dt^2} = \frac{d^2T_{xyz}}{dt^2}\tilde{X}' + 2\frac{dT_{xyz}}{dt}\frac{d\tilde{X}'}{dt} + T_{xyz}\frac{d^2\tilde{X}'}{dt^2} \quad (6)$$

,where $\tilde{X}$, $\tilde{X}'$ and T_{xyz} are as follows:

$$\tilde{X} = [\ \tilde{x}\quad \tilde{y}\quad \tilde{z}\quad 1\ ]^T,\quad \tilde{X}' = [\ \tilde{x}'\quad \tilde{y}'\quad \tilde{z}'\quad 1\ ]^T,$$

$$T_{xyz} = \begin{bmatrix} C_zC_y & C_zS_yS_x - S_zC_x & C_zS_yC_x + S_zS_x & D_lC_zC_y \\ S_zC_y & S_zS_yS_x + C_zC_x & S_zS_yC_x - C_zS_x & D_lS_zC_y \\ -S_y & C_yS_x & C_yC_x & -D_lS_y \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$C_i = \cos\rho_i,\quad S_i = \sin\rho_i,\quad (i = x, y, z).$$

The load position (x, y, z) in the coordinate Σ is calculated by using sway angle (α, β), boom tip position in the Σ $(\tilde{x}, \tilde{y}, \tilde{z})$ and Eq. (7).

$$x = \tilde{x} + l\sin\tilde{\beta}\cos(\theta + \tilde{\alpha}) \quad (7)$$
$$y = \tilde{y} + l\sin\tilde{\beta}\sin(\theta + \tilde{\alpha}) \quad (8)$$
$$z = \tilde{z} - l\cos\tilde{\beta} \quad (9)$$

The dynamics of the rotary crane is calculated by using lope's tension F and Eqs. (11)-(12).

$$m\ddot{x} = -F\sin\tilde{\beta}\cos(\theta + \tilde{\alpha}) \quad (10)$$
$$m\ddot{y} = -F\sin\tilde{\beta}\sin(\theta + \tilde{\alpha}) \quad (11)$$
$$m\ddot{z} = F\cos\tilde{\beta} - mg \quad (12)$$

3.2 Brief Ship Model

A brief ship model is easily built as 2nd order transfer function using Computational Fluid Dynamics (CFD), Flow-3D. The derivation process of the brief ship model is shown in literature(N.Yong Jian, 2011). When ship sway angle ρ_i is output and torque added to ship T_i is input, transfer function $G_{\rho x}(s)$ and $G_{\rho y}(s)$ can be respecting presented as follows:

$$G_{\rho_x}(s) = \frac{K_x\omega_{nx}}{s^2 + 2\zeta_x\omega_{nx}s + {\omega_{nx}}^2} \quad (13)$$
$$G_{\rho_y}(s) = \frac{K_y\omega_{ny}}{s^2 + 2\zeta_y\omega_{ny}s + {\omega_{nx}}^2} \quad (14)$$

Now, damping ratio ζ_i , natural frequency ω_{ni}, and gain K_i must be identified $(i = x, y)$. Conventionally, these parameters must be identified by experiments, but in this research, parameters can be identified by computer simulation using a virtual plant comprised of CFD model (Flow 3D) and rotary crane model. This is a large advantage in this research. Concretely, while transfer of rotary crane is executed using a virtual plant, inclination angle of shipboard is calculated. Parameter identification is carried out by Least Square Method using Simplex Method such that inclination angle of shipboard by brief model matches with that of a virtual plant. The parameter values obtained by this method are as follows:

Table 2: Parameters of the shipboard crane.

Symbol	Appellation	Value
m_L	Mass of the load	17000 [kg]
L_B	Length of the boom	37 [m]
H_c	Height of the turn table	3.0 [m]
l	Length of the rope	30 [m]
m_S	Mass of the ship	1500000 [kg]
L_S	Length of the shipboard	52 [m]
B_S	Width of the shipboard	19 [m]
H_S	Height of the shipboard	3.3 [m]
D_l	Distance from center of the ship to the crane	20 [m]

$$K_x = 2.177 \times 10^{-9},\quad \zeta_x = 0.0677,\quad \omega_{nx} = 2.597$$
$$K_y = 2.364 \times 10^{-10},\quad \zeta_y = 0.0764,\quad \omega_{ny} = 1.964$$

Furthermore, sway angle is resolved x, y component and these are added to the boom tip position of the rotary crane model. In this way, the shipboard crane model is obtained.

3.3 Simulation

For the validation of the shipboard rotary crane model, its behavior was compared with virtual plant using Flow-3D. Parameters of the shipboard rotary crane are shown in Table 2. Transform pattern is shown in Table 3.

Table 3: Rotary transfer pattern using simple mathematical model.

	Slew velocity [rad/s]	Initial slew angle [rad]	Target slew angle [rad]
Pattern 1	0.05	π	$\pi/2$

Figure. 3 shows the transportation trajectory of the suspended load of the constructed model and the virtual plant. By these results, reproducibility for using training simulator was well achieved and this model was employed for training simulator.

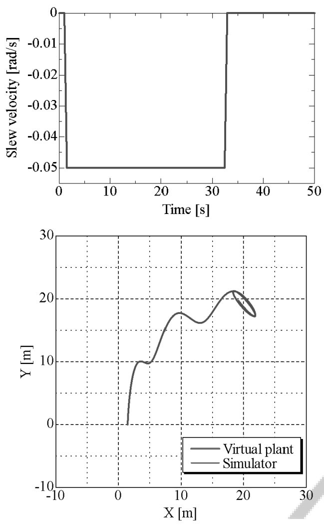


Figure 3: Comparison between Virtual plant and training simulator.

4 CONTROL INPUT

In this section, sway suppression input for teaching to operator is explained. The characteristics of optimal input for teaching operator are shown as follows(T.Iwasa and Y.Noda, 2010),(A.Tsutsui, 1998),(M.Kurimoto, 2009):

- Operation method can master as a formal knowledge.
- Operator can estimate operating timing or operating quantity from motion of a crane or suspended load.
- Operating method is simple.

Formal knowledge is technique or knowledge such as anyone can deduce to only one answer from some rule. On the other hand, implicit knowledge is technique or knowledge which must rely on so-called ”hunch” or ”experience”, and this knowledge complicates acquirement of crane operation. So, implicit knowledge must be removed from training system. In this paper, a preshaping method and a Straight Transfer Transformation (STT) are proposed as operating method satisfying these conditions.

4.1 Preshaping Method

Preshaping method(N.Yong Jian, 2011)(T.Sasaki and K.Terashima, 2013) is well-known vibration suppression method that input opposite signal for the first input signal. In Fig. 4, solid line shows response without second input signal, while dotted line shows response with second input signal. Dotted line is the suppressed vibration by second input signal and arrows show impulse input signal.

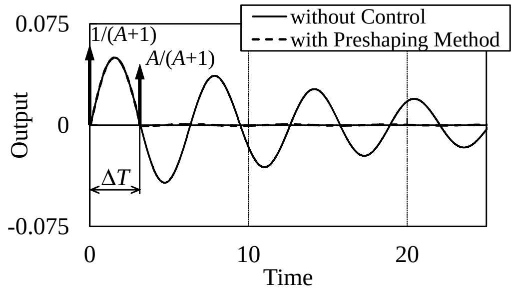


Figure 4: Principle of preshaping method.

4.2 Straight Transfer Transformation

The present transfer using a rotary crane in actual sites mainly uses rotary motion. However, because centrifugal force is generated due to the rotary motion, load is largely swayed, and it takes a long time to suppress the load's sway. On the other hand, by using simultaneous control of rotary and luffing motion, a Straight Transfer Transformation (STT) method (see K. Terashima, et al.[2007] and Y. Shen et al.[2004]) where a load is carried out straightly on X-Y plane from a start point to end was proposed. By using this transfer method, load's sway is restricted in the straight direction only which is the transfer direction. Thus, design of an anti-sway control for transfer is made easier. In this paper, the STT method is adopted. The control velocity reference for STT is calculated along the straight transfer from start to end. Then, its reference on straight line is respectively decomposed to each velocity reference of X-axis direction and Y-axis direction. Furthermore, using Jacobi Matrix which is derived from the relation between tip position of boom, and rotary and luffing angle of crane, each velocity is transformed into rotary velocity and luffing velocity of rotary crane, which finally becomes the control input of the rotary crane. The detail is described in the literature (see Y. Shen et al.[2003] , K. Terashima, et al.[2007] and Y. Shen et al.[2004]).

4.3 Transport Simulation

For the validation of controlled performance, we have done transportation simulation. Control aim is to converge within 0.3 m sway. Transportation trajectory, velocity reference, rotary and luffing velocity input, residual sway and ship sway are shown in Fig. 6. By seeing transportation trajectory, you know that suspended load is rectilinear transported and sway of suspended load is suppressed within amplitude of 0.3 m at the target position. By the result, it is clean that control is well successful.

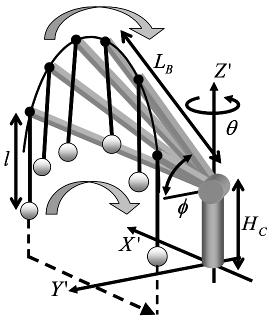


Figure 5: Concept of Straight Transfer Transformation (STT).

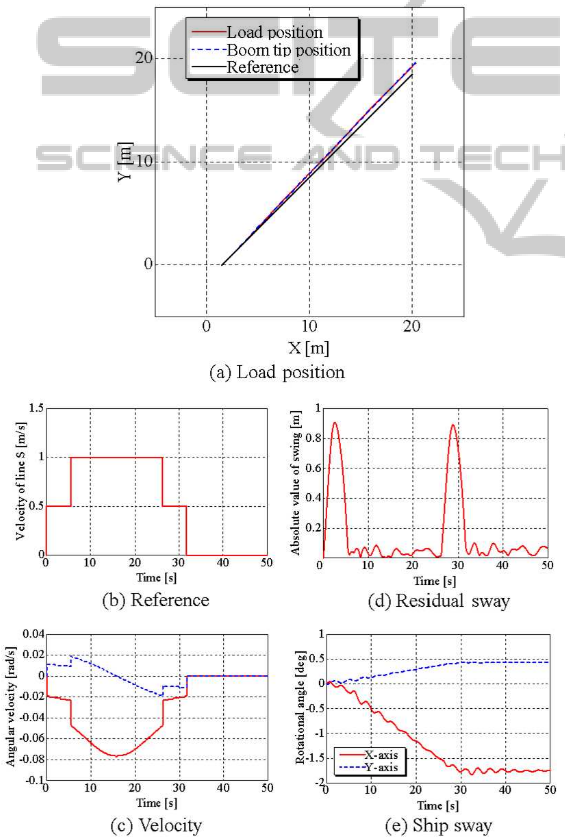


Figure 6: Simulation result of STT with preshaping.

5 TEACHING TYPE TRAINING SYSTEM BY INFORMATION GUIDANCE

In this section, teaching method of sway suppression proposed in last section is presented. In particular, we have developed simulator as target that is an efficient teaching for implicit knowledge.

5.1 Visual Information Teaching

In this section, a training system that converts control input information to visual information and teaches it, is proposed(Attir, 2006)(M.Radjaipour, 2005). This system uses simulator display. We have paid attention to the position of the joystick, and operating position of the joystick is shown as a filled circle on the simulator display (Fig. 7). In addition, a cross cursor shows ideal position trajectory of the joystick. A horizontal axis shows rotary angular velocity input and vertical axis shows the boom luffing angular velocity. Considering the state of the load swing and rope motion leads in the field of view, the visual guidance information was arranged near the suspended load. Operator operates the joystick as tracking a filled circle to a cross cursor. So, operator can easily replicate the sway suppressing input.

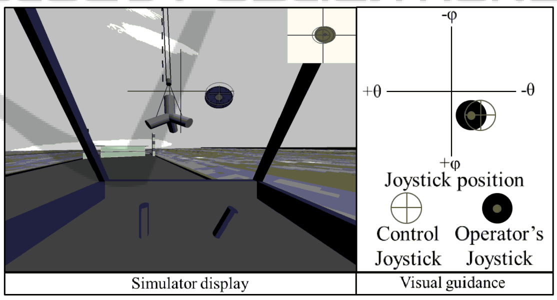


Figure 7: Visual guidance training system.

The flow of this system is shown in Fig. 8. Block diagram of the joystick maneuvered by operator is shown the above diagram in Fig. 8. Diagram of the joystick controlled is shown in the below side. Firstly, the velocity input signal that is given by maneuvering of operator is converted to angle information for joystick. Next, angle information for joystick is converted to visual information and it is outputted on the simulator display. Indicating operation of the sway suppressing, the information is outputted as joystick that is maneuvered by operator. By outputting the both simultaneously, training system by visual teaching is built.

5.2 Haptic Information Teaching

In this part, haptic information teaching system using active joystick is proposed. If operating angle of the joystick deviates from ideal angle over certain angle, active joystick feeds back force of correct angle to op-

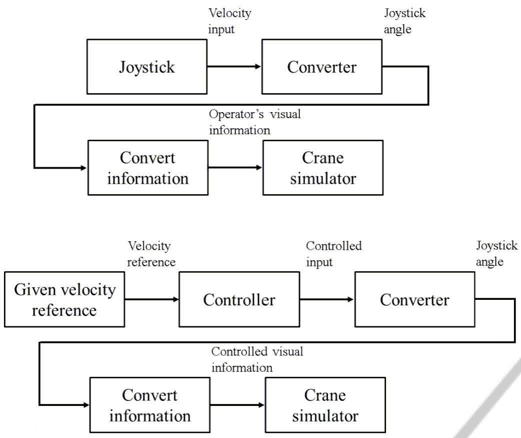


Figure 8: Block diagrams of visual teaching system.

erator's hand (Fig. 9). Operator can spontaneously train, when operated joystick receive force.

The flow of this system is shown in Fig. 10. Firstly, sway suppression input that is obtained in advance and velocity input signal of the joystick that is maneuvered by operator are compared. The force is returned to operator by depending on the result of the comparison. If needed, joystick angle is outputted and force information is fed back to the joystick.

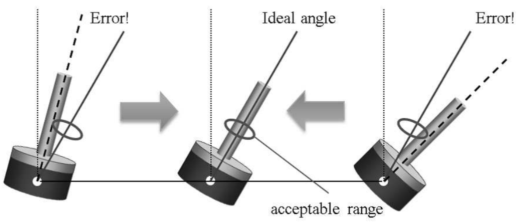


Figure 9: Active joystick motion of haptic teaching system.

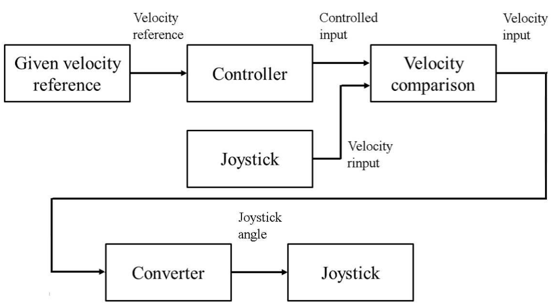


Figure 10: Block diagram of haptic teaching system.

6 SIMULATION EXPERIMENTS OF TRAINING

In this section, experiments for validity verification of the training system are presented. In the experiments, it conducted that transportation test in condition without any teaching after training by the simulator.

6.1 Method of Experiment and Evaluation

Simulation experiments were conducted for human subjects of the following three groups. In addition, human subjects were selected such as that initial operating skill is almost equal condition.

- Group A ($n = 3$): Self training
- Group B ($n = 3$): Visual information teaching
- Group C ($n = 3$): Haptic information teaching

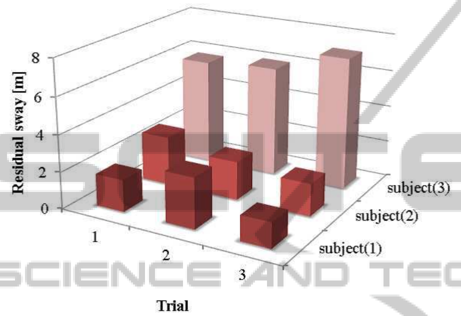
Here, parameter n is the number of human subject. Firstly, transport test without teaching is conducted 3 times. Next, transport test is conducted 3 times after 3 times trainings and these are configured as 1 set. Moreover, 1 set is conducted. Total 9 times transport tests and 6 times trainings were conducted. Crane specifications in the simulation are shown in Table 4. Experimental content is transport to the target position within 1.0 m with sway suppression. Considering result of STT simulation (in section 4.3) and human operating, and transport time in set to 35.0 sec. Evaluation items set as the absolute value of the residual sway within allowable target position.

Table 4: Parameters of a crane for training use.

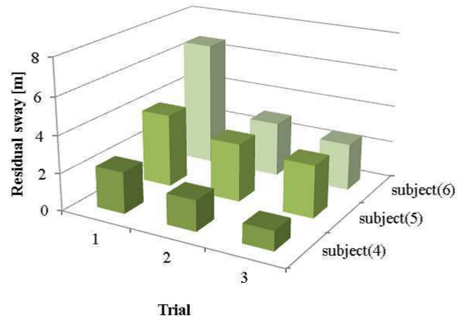
Parameter	Symbol	Value	Units
Rope length	l	30.0	m
Boom length	L_B	37.0	m
Initial slew angle	θ	π	rad
Initial Boom angle	ϕ	$\pi/3$	rad
Slew velocity input	$\dot{\theta}$	0.00.1	rad/s
Boom velocity input	$\dot{\phi}$	0.00.1	rad/s
Initial load position	X, Y	1.5, 0.0	m
Target position	X, Y	20.01.0, 18.51.0	m

6.2 Experimental Result

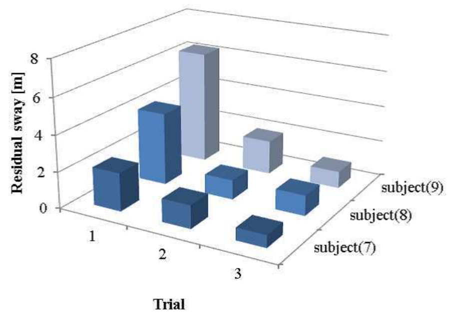
The mean of residual sway of each human subject is shown in Fig. 11. Furthermore, result of subject (1) of Group A in the 3rd set is shown in Fig. 12, result of subject (4) of Group B in the 3rd set is shown in Fig. 13 and result of subject (7) of Group C in the 3rd set is shown in Fig. 14. Residual sway of Group A shows the increasing tendency or the decreasing tendency. Self training doesn’t make constant training effect, because results of residual sway were varied. On the other hand, all results of residual sway of Group B and C are the decreasing tendency. Training effect is advanced by teaching system, and proficiency of operating skill is notably appeared. In particular, haptic teaching system is the highest training effect, because the mean of reduction rate of residual sway is 70% in Group C. The reason is that operator is sensuously able to acquire the operation of joystick by active training, because both visual and haptic sense are used in Group C.



(a) Group A



(b) Group B



(c) Group C

Figure 11: Training result of transfer process.

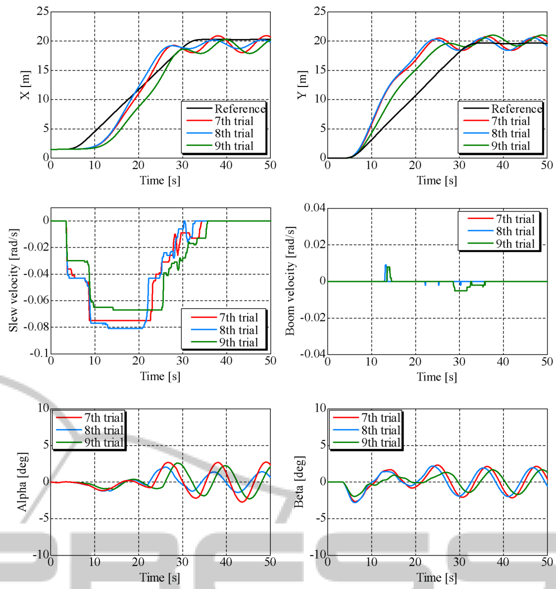


Figure 12: Training result of subject(1) in Group A.

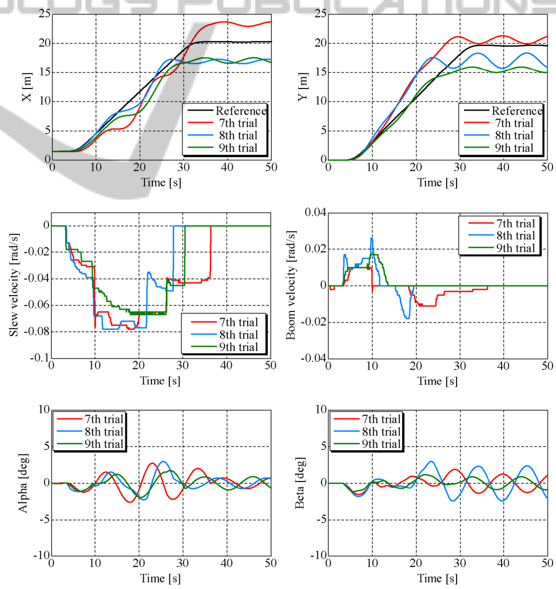


Figure 13: Training result of subject(4) in Group B.

7 CONCLUSIONS

In this study, we built a virtual simulator to train sway suppression skill in shipboard rotary crane. The results are as follows.

1. Movement of suspended load was reproduced by 3D model of shipboard rotary crane based on the mathematical model.
2. Shipboard rotary crane was built by active joy-

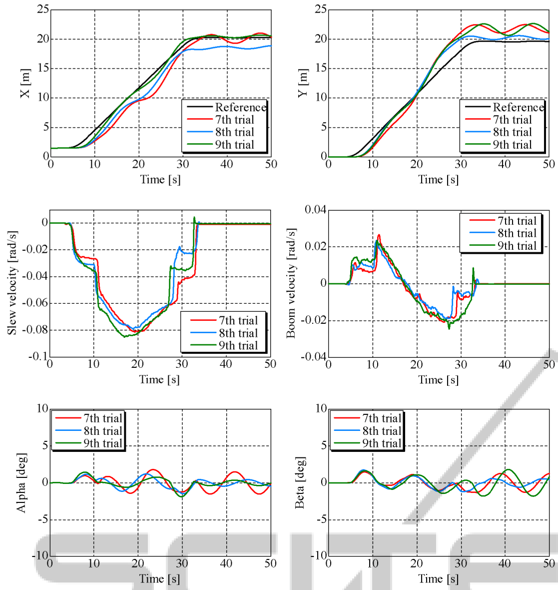


Figure 14: Training result of subject(7) in Group C.

stick for the operation interface and 3D simulator.

3. Sway suppression control was adopted by pre-shaping method, because control calculation is simple.

4. Training system for teaching the operator was proposed. The system presents operator both visual information and haptic force for sway suppression.

5. Effectiveness of the training system was verified by the results of training experiments using the simulator.

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