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Anti-sway Control of an ATC using NN Predictive PID Control

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***Abstract*—In this paper, we develop anti-sway control in proposed techniques for an ATC system. The developed algorithm is to build the optimal path of container motion and to calculate an anti-collision path for collision avoidance in its movement to the finial coordinate. Moreover, in order to show the effectiveness in this research, we compared NNP PID controller to be tuning parameters of controller using NN with 2 DOF PID controller. The experimental results for an ATC simulator show that the proposed control scheme guarantees performances, trolley position, sway angle, and settling time in NNP PID controller than other controller. As result, the application of NNP PID controller is analyzed to have robustness about disturbance which is wind of fixed pattern in the yard. Accordingly, the proposed algorithm proposed in this study can be readily used for industrial applications**

I. INTRODUCTION

Recently, the increase of quantity of goods transport is expected by Super Post-Panamax Vessel's appearance. The growth of international container transport has led to increased demand for quay and terminal capacity in ports all over the world. Therefore, necessity of automation of container port handling equipments are risen to reduce of transfer logistics cost and improvement of terminal operation efficiency. The current development of new automatic container terminal in many countries will reduce the main cost of transportation by sea. World famous companies like ETC from the Netherlands and CTA from Germany are introducing automated loading facilities, such as automatic guided vehicle(AGV) and automated stacking crane(ASC), etc. In their port management systems, thereby an advanced technological system and cost reduction of human resources. Specially, the project aimed at increasing terminal productivity, both with crane that is divided a system of an AGV and an ASC. Moreover, the improvements in stacking height and efficiency were suggested by using container categories. Terminal productivity is a matter of good and appropriate technical systems on the one hand and the right management on the other hand. In the last decade, we have seen an increase in complexity of the technical systems, especially in the introduction of semi-automated systems. Rotterdam's ECT terminal has been leading in this respect with the introduction of an AGV and an ASC at the former Delta-Sealand Terminal in 1992. An automated transfer crane(ATC) control system is required with highest productivity. This tendency may also show the optimal way to solve the employment problems, the cost saving problems and the improvement of efficiency in port systems [2].

To consider nonlinear elements of an ATC, we are to design a controller for crane automatic position and anti-sway. PID controller has been widely used in actual industry because of its convenience and ordinary usage for user. As transfer crane has lots of dynamic characteristics, PID parameters must be changed in varying conditions automatically. An ATC can have controlled using Neural Network(NN) that is one of robust intelligent control theory about nonlinearity [8][9]. Particularly, NN has general character and approximate ability. Most of engineers are progressing research using self-tuner and controller using NN. We will compose an identifier to design a predictor. In order to identification of the crane system was learned enough with input and output of the NN. In these points, it is important to tune the parameters of PID controller adaptively, so we tuned the PID parameters using NN self-tuner. So we constructed PID controller one of 2 DOF PID controller as anti-sway and position controller. The techniques for unmanned traveling system of transfer crane are consisted of an ATC system, automatic landing control system(ALCS), and unmanned operation system(UOS).

In this paper, we would develop an ATC system with anti-sway above three techniques and construct proposed controller in on-line manner. The simulation and experimental results are shown that an ATC system controlled by the proposed controller has better driving performances and anti-sway than the others.

II. MODELING OF AN AUTOMATED TRANSFER CRANE

In this paper, we assume that the considered overhead crane system is satisfied with the following conditions:

(1) An ATC supposes that do only plane moment, that is, the sway of container suppose that happen in plane made by transfer direction and container of trolley.
(2) Elastic deformation of a transfer crane construction is very small value.
(3) Attenuate influence that is happened in frictional resistance or drive mechanism is microscopic.
(4) The container has hanged down in rope that there is no mass.

Fig. 1 shows the coordinate systems of a overhead crane and its load. In Fig. 1, XYZ is the fixed coordinate system

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and $x_T y_T z_T$ is the trolley coordinate system which moves with the trolley. The origin of the trolley coordinate system is $(x, y, 0)$ in the fixed coordinate system. Each axis of the trolley coordinate system is parallel to the counterpart of the fixed coordinate system. θ is the swing angle of the load in an arbitrary direction in space and has two components, i.e., $\theta = (\theta_x, \theta_y)^T$, where θ_x is the swing angle projected on the $x_T z_T$ plane and θ_y is the swing angle measured from the $x_T z_T$ plane.

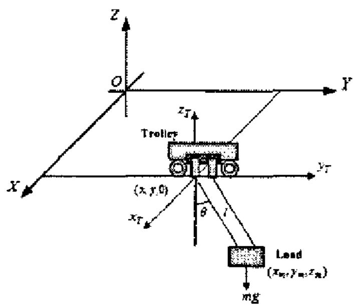


Fig. 1 Coordinate systems of an ATC

The position of the load (x_m, y_m, z_m) in the fixed coordinate system is given by

$$x_m = x + l\sin\theta_x \cos\theta_y \tag{1}$$

$$y_m = y + l\sin\theta_y \tag{2}$$

$$z_m = -l\cos\theta_x \cos\theta_y \tag{3}$$

where l is the rope length. The purpose of this research is to control the motion of both crane and its load. Hence x, y, l, and θ are defined as the generalized coordinates to describe the motion.

The equations of motion of an ATC system are derived using *Lagrange's equation* [1]. Especially, in this research, the load is considered as a point mass, and the mass and stiffness of the rope are also neglected. The kinetic energy of ATC and its load K and the potential energy of the load P are given as follows:

$$K = \frac{1}{2}(M_x \dot{x}^2 + M_y \dot{y}^2 + M_l \dot{l}^2) + \frac{1}{2} m v_m^2 \tag{4}$$

$$P = mgl(1 - \cos\theta_x \cos\theta_y) \tag{5}$$

where M_x, M_y, and M_l are the x (traveling), y (traversing), and l (hoisting) components of the transfer crane mass and the equivalent masses of the rotating parts such as motors and their drive trains, respectively. m is the load mass, g is the gravitational acceleration, and v_m denotes the load speed. Also, Rayleigh's dissipation function is described as follows:

$$D = \frac{1}{2}(D_x \dot{x}^2 + D_y \dot{y}^2 + D_l \dot{l}^2) \tag{6}$$

where D_x, D_y, and D_l denote the viscous damping coefficients associated with the x, y, and l motions, respectively. Then, the equation of motion of an ATC system are obtained by Lagrange's equations associated with the generalized coordinate $q = (x, y, l, \theta_x, \theta_y)^T$.

In practice, the maximum acceleration of an ATC is much smaller than the gravitational acceleration, and the rope length l is kept constant or slowly varying while the cranes are in motion. In this crane system, the object to be controlled is the trolley position, the wire lope length, and the load swing angle. For small swing, $\sin\theta_x \approx \theta_x$, $\sin\theta_y \approx \theta_y$, $\cos\theta_x \approx 1$, and $\cos\theta_y \approx 1$. In this case, with the trigonometric functions approximated, the high order terms in the nonlinear model can be neglected. Then the nonlinear model is simplified to be the linearized model as follows [4][5]:

$$(M_x + m)\ddot{x} + ml\ddot{\theta}_x + D_x \dot{x} = f_x \tag{7}$$

$$(M_y + m)\ddot{y} + ml\ddot{\theta}_y + D_y \dot{y} = f_y \tag{8}$$

$$(M_l + m)\ddot{l} + D_l \dot{l} - mg = f_l \tag{9}$$

$$l\ddot{\theta}_x + \ddot{x} + g\theta_x = 0 \tag{10}$$

$$l\ddot{\theta}_y + \ddot{y} + g\theta_y = 0 \tag{11}$$

This linearized dynamic model consists of the travel dynamics eq. (7) and eq. (10), the traverse dynamics eq. (8) and eq. (11), and the independent load hosting dynamics eq. (9). The travel and traverse dynamics are decoupled and symmetric, which means that the control of a three-dimensional overhead crane is transformed into that of two independent two-dimensional transfer cranes having the same load hoisting dynamics.

III. Path Planning Method of an ATC System

A. Problem statement

In case that an ATC system transport containers in yard, it can be distributed into 5 actuation varieties as shown in Fig. 2. In this figure, the section AB exists an only perpendicular motion of hoist to B point and has the maximum perpendicular velocity, the section BC increases maximally when the velocity of trolley is 0. The other hand, the velocity of hoist decreases maximum to minimum. Also, a swing angle of an ATC system may be 0 at the point C as possible as one can. The swing angle in the section CD exists small and the maximum horizontal moving of trolley exists only. Finally, the section DC and EF have the reverse action between the section AB and BC, respectively.

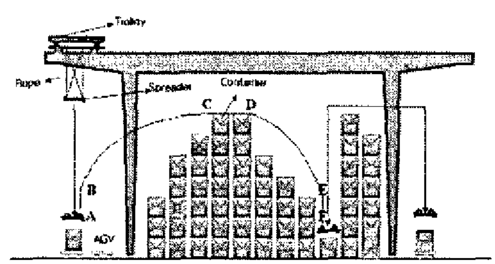


Fig. 2 Each transportation path of an ATC

In this paper, we shall propose the optimal path moving method in order to solving the path moving problem of trolley in an ATC system. Therefore the technique development for investigating the moving paths is required to many researches in order to improve work ability of an ATC system and prevent a loading container from collision in yard. To assign the optimal path for container moving in this research, we propose an effective search algorithm for collision avoidance path which connect both the incoming position A of containers and the outgoing position F and develop the tracking of assigned collision avoidance path and the predictive moving algorithm for transporting containers in the minimum time simultaneously.

B. Path search and minimum distance calculation

In this paper, the containers are divided into lattice format of a rectangular parallelepiped as size and configuration of theirs, and each unit-lattice is composed by the characteristic coordinates (X_i, Y_i) as shown in Fig. 3. Then we will execute the modeling in free space with respect to apply the concept of configuration space based on the distributive map of containers, and then calculate an anti-collision path to be not occurred during the moving motion of container to apply the optimal *best-first search method* for searching the optimal path. Therefore the anti-collision path expresses the knot point located in the conveyance path of container, and then each cross point also represents the reference point of unit-lattice as shown in Fig. 4.

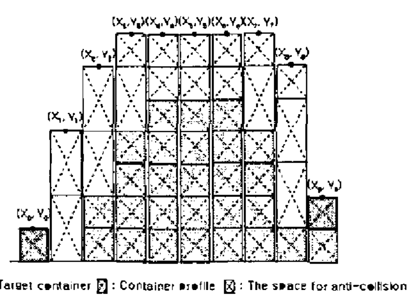


Fig. 3 An imaginary transportation

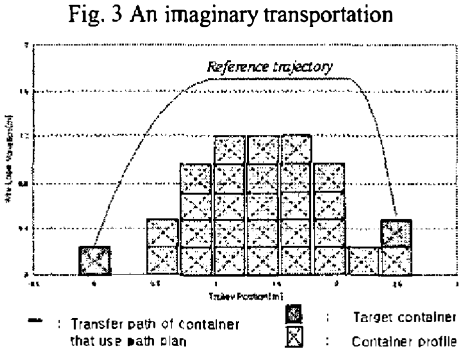


Fig. 4 The path search of reference trajectory

To apply a yard map concept, the method for searching the path, which does not happen to collision between a carried container and various equipments, is summarized as follows:

(1) First, we must frame the yard map to indicate various avoidance distributions in yard. Therefore we use 2-dimensional lattices of a right-angle hexahedron in order to draw the yard map. Each lattice is used to specify proper addresses, i.e., the address (X_i, Y_i) is defined by the i-th address x_i on x-axis and the j-th address y_j on y-axis.

(2) To apply *configuration space technique*, which that the container is described as one point through the extension of container size for moving around a carrying container expressed in the yard map, we reframes the yard map into search space construction.

(3) We apply an optimal method for searching anti-collision path in yard space. In this paper, we select the optimal method for tracking the reference point based on experience information among available search methods.

To track the reference point effectively using Best-first search method [8], we first decide the evaluation function as follows:

$$F = \alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3 \tag{12}$$

where α_i $(i = 1,2,3)$ are weight values. In this paper, the coordinate point of container profile could be set as shown Table 1.

Table 1 The decision parameters of evaluation function

Notations	Descriptions
x_S, y_S	Start node coordinate value
x_G, y_G	Goal node of container coordinate value
x_n, y_n	Standard coordinate value of current node
x_t, y_t	Contiguity node from current node
x_p, y_p	Standard node value

① d_1: It is defined by value that reflects the XY-plane upper from removable contiguity node t to goal node G.

$$d_1 = \sqrt{(x_G - x_t)^2 + (y_G - y_t)^2} \tag{13}$$

② d_2: It is defined by the orthogonal distance to line segment that connects the start node S and the goal node G in contiguity node t projected XY-plane upper to altitude as follows:

$$d_2 = \frac{|ax_t + by_t + c|}{\sqrt{a^2 + b^2 + c^2}} \tag{14}$$

where the equation of straight line is given by:

$$\begin{aligned} & ax + by + c = 0 \\ & a = y_G - y_S, \quad b = x_S - x_G \\ & c = (x_G - x_S)y_S - (y_G - y_S)x_S \end{aligned} \tag{15}$$

③ d_3: The equation of straight line L_1 and L_2 is defined by

$$\begin{aligned} L_1 &: \frac{x - x_p}{l_1} = \frac{y - y_p}{m_1} = \frac{z - z_p}{n_1} = t_1 \\ L_2 &: \frac{x - x_p}{l_2} = \frac{y - y_p}{m_2} = \frac{z - z_p}{n_2} = t_2 \end{aligned} \tag{16}$$

where

$$l_1 = x_n - x_p,\quad l_2 = x_t - x_n$$
$$m_1 = y_n - y_p,\quad m_2 = y_t - y_n \qquad (17)$$
$$n_1 = z_n - z_p,\quad n_2 = z_t - z_n$$

Then an angle d_3 is represented by

$$\cos d_3 = \frac{l_1 l_2 + m_1 m_2 + n_1 n_2}{\sqrt{l_1^2 + m_1^2 + n_1^2}\sqrt{l_2^2 + m_2^2 + n_2^2}} \qquad (18)$$

IV. Controller Design

A. 2 DOF PID controller

In this paper, we will compose PID controller with 2 DOF that contains feedback type as shown in Fig. 5. This controller is very good effectiveness not only the estimation performance of fixing value but also the removal ability of disturbance. Therefore we study the problems to apply the position of an ATC and the anti-sway control of load.

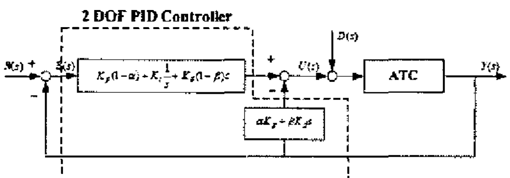


Fig. 5 PID controller with 2 DOF for an ATC

First, the controller output $U(s)$ in Fig. 5 is described by:

$$U(s) = E(s)\{K_p \frac{(1-\alpha)+K_i}{s} + (1-\beta)K_d s\} - (\alpha K_P + \beta K_d s)Y(s) \qquad (19)$$

where K_p, K_i, and K_d are gains of PID controller, respectively, the goal position and the swing angle of load is set by $Y(s)$, and the parameters α and β derive from the transformation of PID controller for various types. Therefore, in this paper, we execute self-tuning using NN about necessary parameters for the design of PID controller. The position error, length error of rope, and swing error are composed by the estimations of 15 parameters. Also, the disturbance $D(s)$ is considered by a strong wind of regular period at all times as follows:

$$F_\omega = p(3\sin\omega t + 7\sin 2\omega t + 5\sin 3\omega t + 4\sin 4\omega t) \qquad (20)$$

where ω is fundamental frequency of wind and p is wind magnitude.

B. NN modeling and predictive system

NNP system is composed of predictive system based on the present input/out information which is learned by executing the modeling learning about plant. The block diagram of neural network modeling learning and the proposed structure of 2-step NNP are shown in Fig. 6 and Fig. 7, respectively.

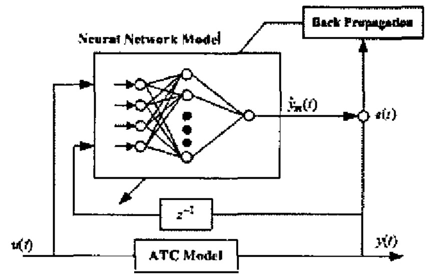


Fig. 6 Modeling of neural network

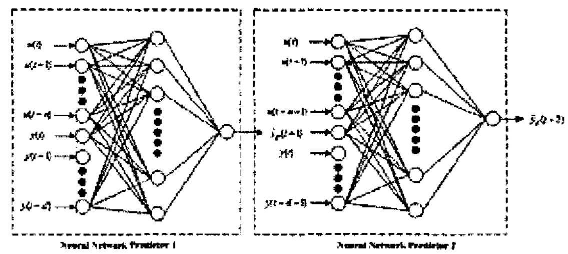


Fig. 7 Structure of neural network predictors

In Fig. 7, the control parameter is the position and angle of trolley. Also, the predictive output get using two NN predictor and the structure consists of 2-step predictor and the identification parameters for NN modeling is described by Table 2.

Table 2 Identification parameters for neural network modeling

		Trolley position	Swing angle
Pattern number		600	600
Node No.	Input No.	40	4
	Hidden No.	6	6
	Output No.	1	1
Learning ratio		0.09	0.09
Moment factor		0.03	0.03
Input parameters		$u(t)$, $u(t-1)$, $\hat{y}(t)$, $\hat{y}(t-1)$	

C. NNP PID controller

In this paper, we will propose the design results for PID controller to have ability to eliminate the disturbance and the performance to pursuer a target in order to control the stacking an ATC system. The proposed NNP PID control system is shown in Fig. 8. In this figure, the system configuration is composed of 3 parts; *i) Neural network predictor, ii) Neural network self-tuner, iii) PID controller.* Neural network predictor can estimate the future output from the input information of current input/output of plant, and then NN self-tuner in order to compensate errors between the calculated predictive output and current output of plant computers parameters of controller through on-line learning scheme. Also, we used PID controller used to an industrial fields widely.

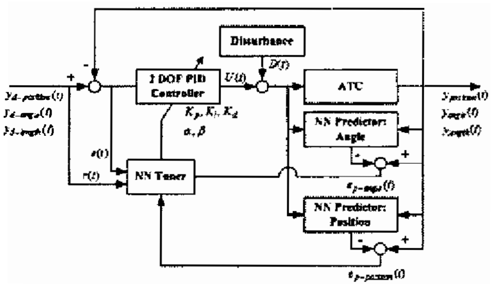


Fig. 8 Block diagram of NNP PID controller

In general, PID controller is known that this controller to have a simple structure is easily realized by linear controller and should be ensure robustness certainly, however the actuate point of control system to require adaptiveness can not be sufficient control performances. To overcome this problem, we will compute parameters of PID controller using NN self-tuner and the structure of NN self-tuner is shown in Fig. 9. Here we use the momentum back propagation learning method and the input layer vector is composed of the error, the deviation of error, the predictive position of trolley, and an angle output and desired value. The activation functions of both hidden and output layers are sigmoid and linear function, respectively. Learning rate and momentum constant of tuner is set to 0.9 and 0.5, respectively. Moreover all weights are set initially 0.5 to be chosen by trial and error.

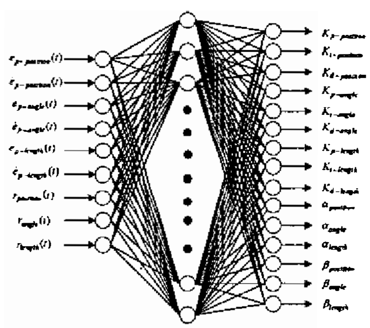


Fig. 9 Neural network self-tuner

In addition, we used NN algorithm to tune the parameters of PID control in online manners.
Also, the disturbance is used in eq. (20) and the estimation function is used error function using the following equations

$$
\begin{aligned}
E &= \frac{1}{2}[y_{d-position}(t) - x(t)]^2 \\
E &= \frac{1}{2}[\theta_{d-angle}(t) - \theta(t)]^2 \\
E &= \frac{1}{2}[y_{d-length}(t) - y(t)]^2
\end{aligned} \tag{21}
$$

Error function E in eq. (21) can be minimized by adjusting weight values. Note that it finds minimum of error function by the gradient descent. Based on the gradient descent method, both output layer and hidden layer are described by:

$$
\begin{aligned}
\Delta W_{jk}(t) &= -\eta \frac{\partial E}{\partial W_{jk}} + \varepsilon \Delta W_{jk}(t-1) \\
\Delta W_{ij}(t) &= -\eta \frac{\partial E}{\partial W_{ij}} + \varepsilon \Delta W_{ij}(t-1)
\end{aligned} \tag{22}
$$

where η and ε are the learning rate and momentum constant, respectively.

The error signal of output layer is

$$
\begin{aligned}
\delta_k &= -\frac{\partial E}{\partial net_k} \\
&= -\frac{\partial E}{\partial y(t+1)} \frac{\partial y(t+1)}{\partial u(t)} \frac{\partial u(t)}{O(k)} \frac{\partial O(k)}{\partial net_k}
\end{aligned} \tag{23}
$$

Then, using the chain rule, the update weights between hidden layer and output layer is calculated by:

$$\Delta W_{jk}(t+1) = \eta \delta_k O_j + \varepsilon \Delta W_{jk}(t) \tag{24}$$

Note that the error signals of each node for output layer, the Jacobian of system, and the derivative equation of output layer for each NN node are described by our previous researches, respectively [3][7].

V. Experimental Results

To evaluate the NNP PID controller proposed in this paper, we execute experimental results for an ATC simulator and describe the relative analysis for the position of container, sway control, and the load variation for disturbance and container using PID controller and NNP PID controller.

Fig. 10 shows the structure of an ATC simulator system built for this study and the schematic diagram for experimentation is shown in Fig. 11. The ATC system is composed of four parts; *i) control part*, *ii) driving part*, *iii) communication part*, and *iv) sensor part*, respectively.

Fig. 10 ATC simulator system

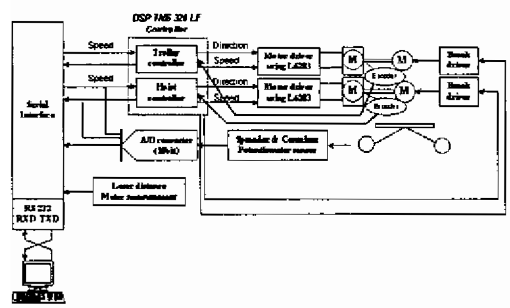
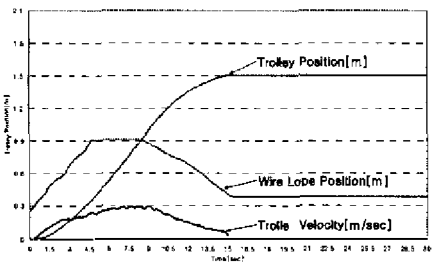
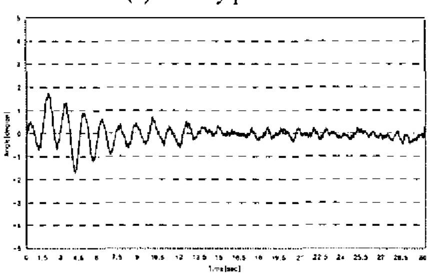


Fig. 11 Schematic diagram of an ATC System

The ATC simulator system is about 3.5 meters long, 0.5 meters wide, and 1.6 meters high. Also, the simulator container is about 0.6 meters long, 0.2 meters wide, 0.1 meters high. The proposed control scheme has been applied to the control of simultaneous traveling, traversing, and hoisting motions of an ATC for performance evaluation. The overall control system was shown in Fig. 8.

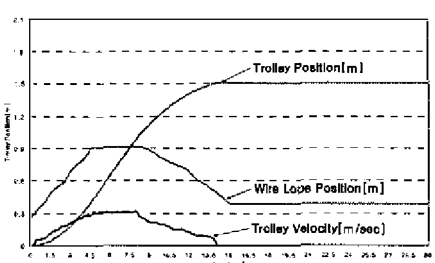


(a) trolley position

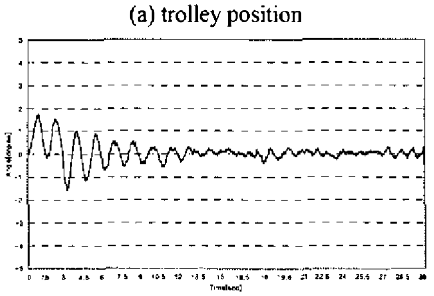


(b) angle

Fig. 12 Experimental results with response characteristics of PID for disturbance(a wind force)



(a) trolley position



(b) angle

Fig. 13 Experimental results response characteristics of NNP PID for disturbance(a wind force)

Fig. 12 and Fig. 13 show the experimental results with response characteristics of PID and NNP PID controllers, respectively. In this figure, the weight of container increases about 15[kg] and the disturbance is also added by an initial state of disturbance. Compared with each term, we know that NNP PID controller decreases more 0.1862[degree] than PID controller and the amplitude of swing angle also decrease more 0.049[degree] than PID controller.

VI. Conclusions

In this paper, we develop anti-sway control in proposed techniques for an ATC system. First, the developed algorithm is to build the optimal path of container motion and to calculate an anti-collision path for collision avoidance in its movement to the finial coordinate.

In order to show the effectiveness in this research, we compared NNP PID controller to be tuning parameters of controller using NN with 2 DOF PID controller. The experimental results show that the proposed control scheme guarantees good performances, trolley position, sway angle, and settling time in NNP PID controller than other controller. That is, trolley position and sway angle improved 60.12%, 48.28%. Also, NNP PID controller was improved than ES-tuned PID controller. Moreover trolley position and sway angle was improved 91.75%, 58.67%.

VII. Acknowledement

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