Comparison of Anti-sway Gantry Crane Control System based on PID and Fuzzy Logic Control

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Keywords: Anti-sway, Gantry Crane, Fuzzy Logic, Proportional-Integral-Derivative.

Abstract The development of industry involves automation as the core of the manufacturing process and material handling. One of the automatic applications called gantry crane used for things moves from one place to another place. The problem arises when the gantry crane makes a movement to carry some loads. The cable which connects the crane and load may make sway continuously. This sway is unwanted because it will be dangerous to people or the environment near the gantry crane. Moreover, the load could be dropped, or the worse thing is the cable could be broken. As a result of that, the sway should be eliminated faster. This research purposed to design an antisway system that will reduce or make the sway is gone quickly. PID and Fuzzy Logic are used as the method of the controller for the implementation of anti-sway. The result showed that the sway could decrease in two aspects. The first is the duration of sway reduced from 158,35 to 3,885 second by fuzzy logic and from 82 to 7 seconds by PID. The second is maximum sway was also reduced from 17,52 to -8,09 by fuzzy logic and from -12,59 to 4.22 by PID.

1 INTRODUCTION

Gantry crane is used in many industries or harbor to do load movement easily. The conventional crane sometimes is not safe because there is a way which makes an operator must be careful to control the crane manually. The sway is hardly attenuated, and it becomes a challenging problem for engineers on how to design a control system that works for reducing the sway in gantry crane. The system which can decrease and attenuate the sway is called anti-sway. It will run automatically together with control of crane's position.

Some methods have been developed to handle or to implement anti-sway. There are fuzzy logic controller [1], [2], and PID [3]. However, we do not believe in the assumption that a controller method is better than another method. So, this research would compare two popular methods applied in the anti-sway system. In the experiment, the response of the sway degree would be showed and plotted with different parameters and conditions.

2 GANTRY CRANE

Cranes are usually used for moving heavy goods transportation in harbor, manufacture, and high construction building project. One of the types of cranes is a gantry crane. That has two holders on both sides and one rail between the holders. Most of the gantry cranes are operated manually, which may swing the heavy load like a pendulum. The swing needs to be balanced quickly so that the sway will not be harmful, and the goods are moved faster. Figure 1 below shows the prototype of the gantry crane used in this research.

Figure 1: Prototype of Gantry Crane.

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In this prototype, the control method is used as the control of position and anti-sway. Generally, the system is a closed-loop with two feedbacks. One sensor is used as a sway sensor that detects the angle of sway and another one used as displacement sensing. Figure 2 describes the block diagram for control of position with anti-sway.

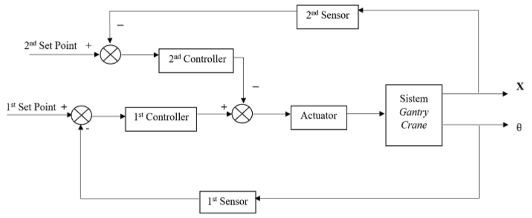

Figure 2: Closed-Loop Blok Diagram.

Based on Figure 2, it is showed that the overall system also has two controllers and one actuator. The DC motor is used as the actuator. The output of both controllers would be accumulated as a PWM signal and fed into the actuator.

3 GANTRY CRANE MODELING

Figure 3 shows the physical model and all of the parameters used for deriving the mathematical model. The input is force applied in the cart while the outputs are θ (the angle of sway) and x_1 (the position of cart).

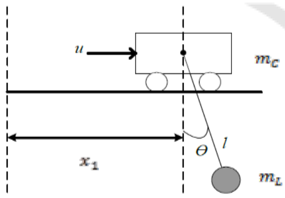

Figure 3: Gantry Crane Model.

Note : m_C = Cart mass (kg)
m_L = Crane mass (kg)
l = Rotational axis length to center of mass (m)
θ = Pendulum vertical angle (rad)
g = Acceleration of gravity (m/s2)
x_1 = Cart coordinate position (m)

By using Newton's second law the dynamics of the Gantry Crane equation can be derived, such as the horizontal direction cart motion as in the following equation.

$$\sum F\sin\theta + u = m_c \frac{d^2x1}{dt^2} \tag{1}$$

As for the cart motion in the vertical direction as in the equation.

$$F\cos\theta + m_c g = 0 \tag{2}$$

For horizontal direction load motion, the gantry crane dynamics equation can be derived as in the equation:

$$m_L \frac{d^2(x_1 + l\sin\theta)}{dt^2} = -F\sin\theta \tag{3}$$

As for the vertical direction load motion as in the equation.

$$m_L \frac{d^2(l\cos\theta)}{dt^2} = -F\cos\theta + m_L g \tag{4}$$

From equations (1) and (3) obtained.

$$m_c \frac{d^2x1}{dt^2} = u - m_L \frac{d^2(x_1 + l\sin\theta)}{dt^2}$$

$$m_c \frac{d^2x1}{dt^2} + m_L \frac{d^2(x_1 + l\sin\theta)}{dt^2} = u \tag{5}$$

From equations (3) and (4) obtained.

$$\begin{gathered} m_L \frac{d^2(l\cos\theta)}{dt^2} = \frac{\cos\theta}{\sin\theta} m_L \frac{d^2(x_1 + l\sin\theta)}{dt^2} + m_L g \\ m_L \frac{d^2(l\cos\theta)}{dt^2}\sin\theta - m_L \frac{d^2(x_1 + l\sin\theta)}{dt^2}\cos\theta \\ = m_L g\sin\theta \end{gathered} \tag{6}$$

That,

$$\frac{d^2(x_1 + l\sin\theta)}{dt^2} = \ddot{x}_1 + l\ddot{\theta}\cos\theta - l\dot{\theta}^2\sin\theta \tag{7}$$

$$\frac{d^2(l\cos\theta)}{dt^2} = -l\ddot{\theta}\sin\theta - l\dot{\theta}^2\cos\theta \tag{8}$$

From equations (5), (6), (7), dan (8) obtained,

$$(m_L + m_c)x_1 + m_L l(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) = u \tag{9}$$

$$m_L\ddot{x}_1\cos\theta + m_L l\ddot{\theta} = -m_L\sin\theta \tag{10}$$

$$x_1\cos\theta + l\ddot{\theta} = -g\sin\theta \tag{11}$$

Equations (9) and 10) are written with the state space as follows.

$$\begin{bmatrix} m_L + m_c & m_L l\cos\theta \\ m_L\cos\theta & m_L l \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} m_L l\dot{\theta}^2\sin\theta) + u \\ -m_L\sin\theta \end{bmatrix}$$

$$\begin{bmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{u + m_L\sin\theta(l\dot{\theta}^2 + g\cos\theta)}{m_c + m_L\sin^2\theta} \\ \frac{u\cos\theta + m_L\sin\theta(g + l\dot{\theta}^2\sin\theta) + g\, m_c\sin\theta}{l(m_c + m_L\sin^2\theta)} \end{bmatrix} \tag{12}$$

To facilitate writing, the mathematical model of the gantry crane system can be expressed in four state vectors namely $x = [x_1 \quad x_2 \quad x_3 \quad x_4]$, that x_1 is the position of the cart, x_2 is the angular position of the crane rope, x_3 is the velocity of the cart, dan x_4 is the angular velocity of the crane rope.

Cart velocity (x_3) is the first derivative of the cart position (x_1), and the angular velocity of the crane rope (x_4) s the first derivative of the angle of the crane rope (x_2). From the equation that has been derived, then the mathematical model in the form of state equation [2] can be written in Equation (13) as follows.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} = \begin{bmatrix} x_3 \\ x_4 \\ \frac{u+m_L \sin x_2 (l{x_4}^2 + g \cos x_2)}{m_c + m_L \sin^2 x_2} \\ \frac{u \cos x_2 + m_L \sin x_2 (g + l{x_4}^2 \sin x_2) + g\, m_c \sin x_2}{l(m_c + m_L \sin^2 x_2)} \end{bmatrix} \quad (13)$$

4 CONTROL SYSTEM DESIGN

4.1 Fuzzy Logic Controller

The mathematical model of gantry crane is a non-linear model. Analytically, the linear control method is hard to be implemented. Even though linearization can be done, but the model is still hard to get it accurately.

Fuzzy Logic was introduced by Lofti Zadeh in 1965. This method is also used for the control method and known as the Fuzzy Logic Controller (FLC). A detailed mathematical model is not necessary if FLC is used as a controller, because FLC is designed by finding how much or big the data measurement is possible. So, the difficulty of the FLC method is to find all of the parameters which would give the best performance.

The fuzzy method used is the Takagi Sugeno method. The Takagi Sugeno method produces output in the form of constant values or linear equations. There were 2 FLC in this system, namely FLC angles and FLC position. FLC position has two inputs were an error (e) position and delta error (Δe) position with output in the form of PWM value. Whereas the FLC angle also has two inputs were error (e) angle and delta error (Δe) angle with output PWM value. The two PWM outputs would be added up and become the input for the movement of the DC motor.

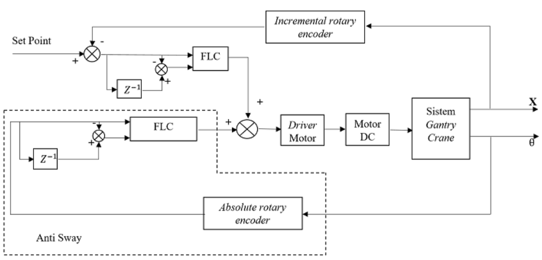

Figure 4: Diagram Block of Gantry Crane System.

There are three fuzzy sets for each FLC, namely error (e), delta error (Δe), and PWM output values, as shown in Figure 5. Then nine rules will be arranged for each FLC, which can be seen in Table 1 in full.

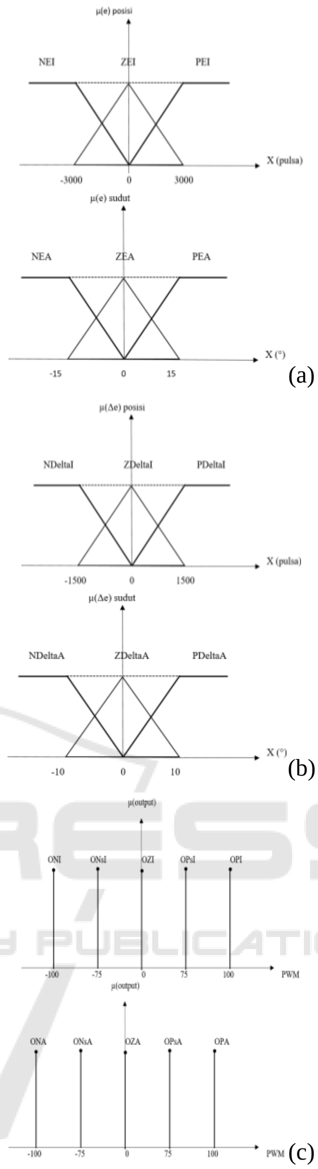

Figure 5: Fuzzy input membership function. (a) position and angle error (b) delta position and angle error, (c) PWM value of the position, and angle output.

The rules used in the position FLC and angle FLC are the same. These rules are obtained based on the system characteristic graph shown in Figure 6 below:

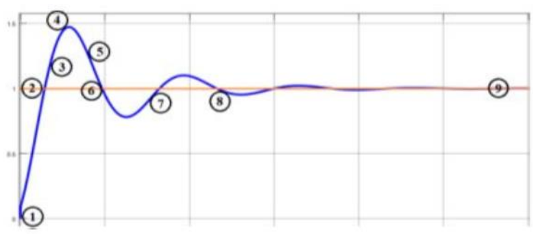

Figure 6: Fuzzy input membership.

Table 1: Fuzzy logic rules position and angle.

Δe \ e	NE	ZE	PE
NDelta	ON 3	ONs 2	OP 7
ZDelta	ON 4	OZ 9	OP 1
PDelta	ON 5	OPs 6	OP 8

4.2 PID

PID control (Proportional-Integral-Derivative) was a controller with feedback that is commonly used in industrial control systems. The PID control system has three parameters, namely Proportional (P), Integral (I), and Derivative (D). PID control continuously calculated the error value or error, which is the difference between the desired setpoint and the measured process variable [5].

The general PID control equation could be written as follows.

$$u(t) = K_p\, e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (14)$$

That:
Kp : Proportional gain
Ki : Integral gain
Kd : Derivative gain
e : error = Ysp - Ym
Ysp : setpoint
Ym : Process variable
t: Time

Three parameters of the PID control have outputs with the following characteristics:

- Parameter P: proportional to the error at t at this time.
- The parameter I: proportional to the integral from error to t at this time, which can be interpreted as the previous error accumulation.
- Parameter D: can be interpreted as a possible future error.

The PID control can be represented in the form of a block diagram in Figure 7 as follows:

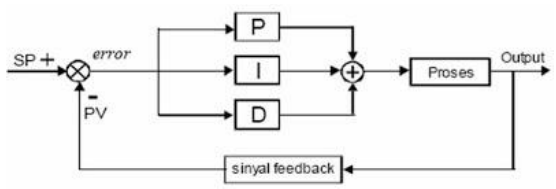

Figure 7: Blok Diagram PID Control.

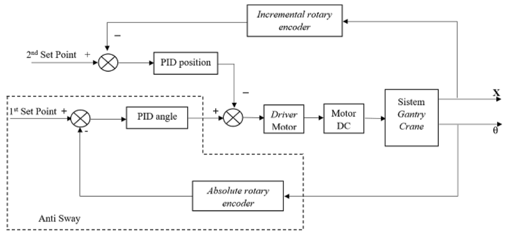

Figure 8: Diagram Block of PID Control System.

5 EXPERIMENT AND ANALYSIS

Anti-sway gantry crane system testing was carried out using a rope length of 60 cm and a load of 0.5 kg. There were two methods used, namely fuzzy logic control and PID control.

5.1 Fuzzy Logic Control Experiment

The experiment of the whole system was done by paying attention to two testing parameters, namely testing without using a method and using the fuzzy logic control method.

1) The Experiment Without Using Fuzzy Logic Control

This test was carried out to determine the system response without using control methods. The system was given input in the form of a PWM value of 90, which corresponds to the PWM output when the system uses the FLC control method when the system first runs. The setpoint of the intended position was 2500 pulses or equivalent to 37.7 cm. This test was done by letting the crane rope swing to the point set at an angle of 0°. The test results should be seen in the following Figure 9 and Figure 10.

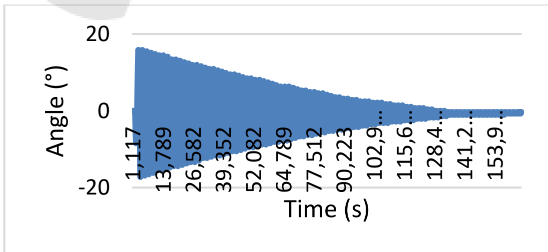

Figure 9: Angular Response Graph Without Control Method.

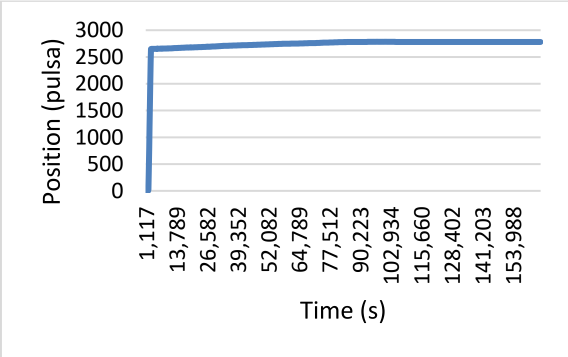

Figure 10: Position Response Graph Without Control Method.

Based on Fig. 9 and Fig. 10, it could be seen that the system without using the PID control has the farthest deviation angle of -17.52° and takes 158,35 seconds to achieve stability. While the system's position without using the PID control exceeds the setpoint specified at counter 2500. So that the PID control method was needed so that the angle deviation was <10° and the cart position approached the setpoint.

2) The Experiment Using Fuzzy Logic Control

This test was conducted to determine the accuracy of the results of the compiled algorithm. In this test, the value of membership function input was used, namely error € angle of the crane rope and delta error (Δe). The negative value on error € showed the rotation of the crane rope, which is counterclockwise. The membership function output value has three variations, namely the 1st output, the 2nd output, and the 3rd output. The response of the angle FLC system to each output variation was shown in the following Figure 11.

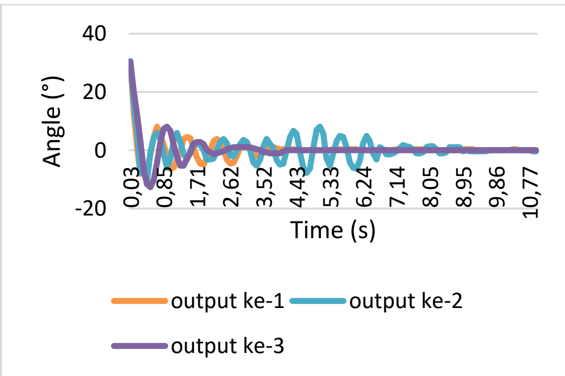

Figure 11: Angular Response Graph with Different Fuzzy Logic MF Outputs.

Table 2: The experiment with Different Fuzzy Logic MF Outputs.

MF Output	ON	ONs	OZ	OPs	OP	Time (s)	Farthest Deviation (°)
Ke-1	-100	-75	0	75	100	3,885	-8,09
Ke-2	-150	-75	0	75	150	9,954	-10,56
Ke-3	-75	50	0	50	75	4,066	12,67

Based on Table 2 above, it could be seen that at the time of the membership function (MF), the 1st fuzzy logic output the system could achieve stability after 3.885 seconds and has the farthest deviation of -8.09°. The selection of MF fuzzy logic output values was based on the parameters of the pendulum angle response to time, where the MF value of the 1st fuzzy logic output was chosen because it requires a faster time to achieve stability compared to other values.

The response of the position FLC system to each output variation is shown in the following Figure 12.

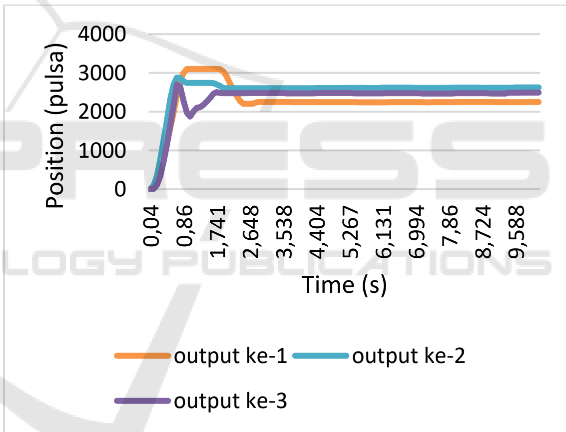

Figure 12: Position Response Graph with Different Fuzzy Logic MF Outputs.

Table 3: The experiment with Different Fuzzy Logic MF Outputs.

MF Output	ON	ONs	OZ	OPs	OP	Time (s)
Ke-1	-75	-50	0	50	75	2,831
Ke-2	-150	-75	0	75	150	1,833
Ke-3	-100	-75	0	75	100	1,833

Based on Table 3 above, it could be seen that during the membership function (MF), the 2nd and 3rd fuzzy logic output, the system could achieve stability after 1,833 seconds. But the closest to the setpoint (2500 pulses) was the 2nd fuzzy logic output.

The selection of MF fuzzy logic output values was based on the parameters of the position of the cart response to time, where the MF value of the 2nd fuzzy logic output was chosen because it requires a faster time to achieve the lowest stability and steady-state error.

5.2 PID Control Experiment

The experiment of the whole system was carried out by paying attention to two testing parameters, namely testing without using a method and using the PID control method.

1) The Experiment Without Using PID Control

This test aims to determine the angle and position response to the time before PID control methods are given. In this test, the setpoint for the cart position was determined by the value of 2500 pulses. After that, the test was carried out to see the farthest corner deviation produced and the position of the cart when not using the PID control method. The results of these tests could find out how long the system reaches stability.

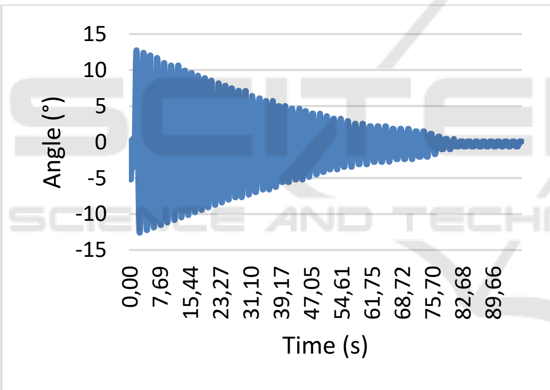

Figure 13: Angular Response Graph Without PID Control Method.

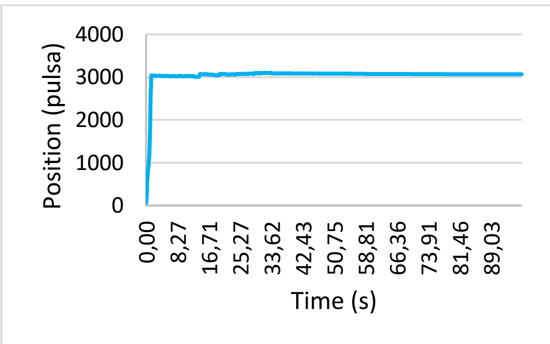

Figure 14: Position Response Graph Without PID Control Method.

Based on Figure. 13 and Figure. 14 it could be seen that the system without using the PID control has the farthest deviation angle of -12.59° and takes 82 seconds to achieve stability while the system's position without using the PID control exceeds the setpoint specified at counter 2500. So that the PID control method was needed so that the angle deviation is <10° and the cart position approaches the setpoint.

2) The Experiment Using PID Control

This test aims to determine the design of the Kp, Ki, and Kd values of the system to get the best response so that the system can achieve setpoint and stability. In this test, PID parameters were tested at the angle of the pendulum and cart beam position.

The steps of this test were done by trial and error on the system. Kp, Ki, and Kd values were given alternately, then taking into account the pendulum angle's response to time and cart's position to time. To be able to find out the results of testing could be seen in Figure 15 and Table 4.

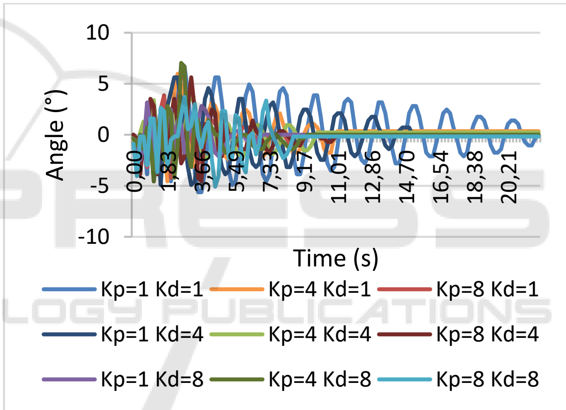

Figure 15: Angular Response Graph with Different Kp and Kd Outputs.

Table 4: The experiment with Different KP AND KD Outputs.

No	Kp	Kd	Time (s)	Farthest Deviation (°)
1.	1	1	21,8	6,69°
2.	4	1	10,9	5,98°
3.	8	1	9,2	5,98°
4.	1	4	15,2	5,63°
5.	4	4	9,9	3,75°
6.	8	4	11,1	5,63°
7.	1	8	7	4,22°
8.	4	8	9,4	7,04°
9.	8	8	8,7	4,04°

Based on Table. 4 above could be seen that when the value of Kp = 4 and the value of Kd = 4 reaches stability after 9.9 seconds and has the furthest deviation of 3.75°. However, when the Kp value = 1 and the Kd value = 8, the system could reach stability after 7 seconds and has the farthest deviation angle of 4.22°. So that the selection of Kp and Kd values following the system designed was Kp = 1 and Kp = 8. The choice of Kp and Kd values was based on the parameters of the pendulum angle response to time, so that the values of Kp = 1 and Kd = 8 require faster time to achieve stability compared to other values and have the farthest corner deviation that was not too large. To find out the position response to time could be seen in Figure 16 and Table 5.

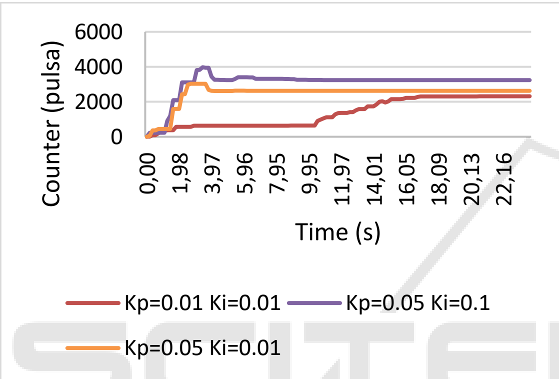

Figure 16: Position Response Graph with Different Kp and Ki Outputs.

Table 5: The experiment with Different KP AND KI Outputs.

No	Kp	Ki	Time (s)	Position (pulsa)
1.	0,1	0,01	14,2	5104
2.	0,01	0,01	23,8	2317
3.	0,05	0,01	7,2	2623
4.	0,05	0,1	12,8	3236

Test results in Table. V, it could be concluded that the value of Kp = 0.05 and Ki = 0.01 could approach the setpoint value determined by counter 2500. Even though the value of Kp = 0.01 and Ki = 0.01 could approach the specified setpoint value, but the time needed by the system reaching setpoint requires a long time, which is 23.8 seconds. So we get the value of Kp =0.05 and Ki = 0.01 so that the system could reach the desired position with a relatively fast time.

6 CONCLUSIONS

From the results of testing and analysis, it could be concluded that this research was able to reduce the sway that occurs in the operation of the prototype gantry crane. The result showed that the sway could decrease in two aspects. The first is the duration of sway reduced from 158,35 to 3,885 second by fuzzy logic and from 82 to 7 seconds by PID. The second is maximum sway was also reduced from 17,52° to -8,09° by fuzzy logic and from -12,59° to 4.22° by PID.

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