# Anti-Sway Control for Haptic Crane for Application of Material Handling by using Active Force Control (AFC)

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*Abstract*— **This paper focuses on anti-sway control system for haptic crane that uses accelerometer and weight sensor as sway sensor and mass calculation of payload. The control method proposed is AFC which is able to control more accurate and robust while transport the payload to another location and at the end of the movement as fast and as accurate as possible. To do this the dynamic mathematical model of the crane is introduced. The result shows that the addition of weight sensor and accelerometer as an additional parameter in AFC loop calculation in the hook gives better performance even with several disturbances than the PID control.**

*Keywords*— **haptic crane, accelerometer, weight sensor, active force control (AFC), disturbance**

## I. INTRODUCTION

In large factories, harbors, or construction sites, it is common to see crane with several types and functions which mainly used to move the payload to the desired location. The process of transporting the payload is done using rope mechanism which is connected to the hoist and hook. Numerous industrial applications, such as the loading and unloading of containers, nuclear waste handling facilities, factory automation and basically in any industry which requires heavy materials to be lifted and moved use crane to do such kind of job. The study of the control of the crane is complex, as different industrial applications require different control systems. Recently designed cranes are larger and have higher lifting capacities and travel speeds. To achieve high productivity and to comply with the safety requirements, these cranes require effective controllers such as anti swing controls. Inertia forces due to the motion of the crane can induce significant payload oscillations. If the oscillations of the payload can be constrained using an appropriate method, there will be a number of benefits such as having greater yield and safety margin, enabling higher operating speed, enhancing work quality and creating greater throughput for a given installed capacity. Besides, most actual systems are influenced by noise and external disturbances including crane. These disturbances such as wind, unstable mounting and others may degrade the performance of the crane [1].

## II. SYSTEM MODELLING

Figure 1 shows the schematic system of a crane. It is considered that the horizontal position of trolley, x, the length of the hoisting cable, *l*, and the sway angle, *θ*. Before analyzing the dynamic motion of the crane into a mathematical model, a number of assumptions are introduced, so that the crane model can be simplified:

- The trolley and the load can either move or oscillate in x-y plane
- The tension force that will cause the hoisting cable to elongate is neglected
- Both the trolley and the payload are considered as point masses.
- The friction between the trolley and the rail is neglected.

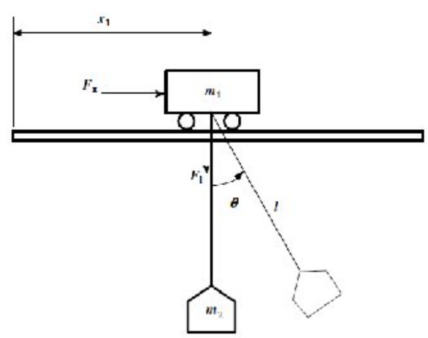


Figure 1: Schematic diagram of a gantry crane

The model of the system is derived using Lagrangian dynamics. The mathematical equation for determining the dynamics of a system using Lagrangian equations is given as:

$$\frac{d}{dt}\left[\frac{\partial L}{\partial \dot{q}_i}\right] - \left[\frac{\partial L}{\partial q_i}\right] = F_i \quad (1)$$

The Lagrangian equation for the system is given as:

$$\boldsymbol{L = T - U} \quad (2)$$

Since $U$ is not a function of $q_i$ $L = L(\dot{q}_i, q_i, t)$ and $U = (q_i, t)$

$$T = \frac{1}{2}m_1\dot{x}^2 + \frac{1}{2}m_2(\dot{x}^2 + \dot{l}^2 + l^2 + 2\dot{x}\dot{l}sin\theta + 2\dot{x}l\dot{\theta}sin\theta) \quad (3)$$

$$U = -m_2 g l cos\theta \quad (4)$$

Where $m_1$ and $m_2$ are the mass of the trolley and load, respectively, and g is the gravitational acceleration. Since the kinetic energy $T$ is of the from $T(q,\dot{q}) = \frac{1}{2}\dot{q}^T D(q),\dot{q}$, where $D(q)$ is a symmetric and positive definite matrix for $l>0$such that

$$D(q) = \begin{bmatrix} m_2 l^2 & m_2 l cos\theta & 0 \\ m_2 l cos\theta & m_1 + m_2 & m_2 sin\theta \\ 0 & m_2 sin\theta & m_2 \end{bmatrix} \quad (5)$$

The following Euler – Lagrange equation can be used when deriving the equations of motion.

$$D(q)\ddot{q} + \left\{\frac{d}{dt}[D(q)]\dot{q} - \frac{\partial V(q,\dot{q})}{\partial q}\right\} + \frac{\partial V(q,\dot{q})}{\partial q} = Q \quad (6)$$

The generalized force $Q$, associated with $q = [\theta, x, l]^T$, be $[0,F_x,F_y]^T$, where $F_x$ and $Fy$ are the forces applied to the trolley in the x-direction and to the suspended load in the $l$-direction, respectively. From (2.3), (2.4) and (2.6), the equation of motion are:

$$F_x=(m_1+m_2)\ddot{x} + m_2 l\ddot{\theta} cos\ \theta + m_2\ddot{l} sin\ \theta + (2m_2\dot{l} cos\ \theta - m_2 l\dot{\theta} sin\ \theta)\dot{\theta} \quad (7)$$

$$l\ddot{\theta}+2\dot{\theta}\dot{l}+\ddot{x}cos\ \theta + gsin\ \theta = 0 \quad (8)$$

$$-F_l=m_2\ddot{l}+m_2\ddot{x}sin\ \theta - m_2 l\ \dot{\theta}^2 - m_2 gcos\ \theta \quad (9)$$

The equations of motion are nonlinear because of the presence of trigonometric terms such as $sin\ \theta$ and $cos\ \theta$ as well as the quadratic term contained in the equations. To perform linearization, assuming that the sway angle is small, then:

$$\theta_0 = 0\ and\ sin\theta \approx \theta_0$$

$$cos\theta \approx 1$$

$$\dot{\theta}^2 \approx 0$$

The tension force of hoisting cable which cause the cable to elongate is neglected, thus:

$$\dot{l} = \ddot{l} = 0 \quad (10)$$

The equations of motion for a linearized model of a crane are represented as follows:

$$F_x = (m_1 + m_2)\ddot{x} + m_2 l\ddot{\theta} \quad (11)$$

$$l\ddot{\theta} + \ddot{x} + g\theta = 0 \quad (12)$$

$$F_l = m_2 g - m_2\ddot{x}\theta \quad (13)$$

## III. SWING ANGLE MEASUREMENT

The level of the slope can be measured by comparing the value of acceleration of the object in a tilted position with the vertical position, called the sinus [4].

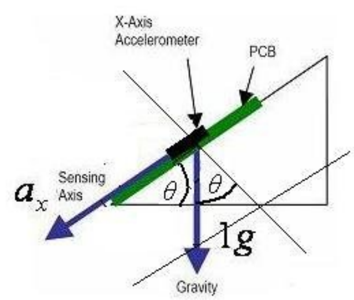


Figure 2: Accelerometer on the incline

From Figure 2 it can be seen the direction and acceleration of an accelerometer on an inclined plane can be formulated in the following equation:

$$\theta = \arcsin\left(\frac{a_x}{1g}\right) \quad (14)$$

## IV. AFC

Load or disturbance on the actuator system essentially is an active force that against the forces generated by the spindle motor. Power generated by motor or actuator generally in a power control system is a output power based on algorithm or methods used.

The more responsive the output power due to disturbance and effects of load the better the control is. Thus, any movement in the robotic control scheme that consider load or disturbance in its operations can be categorized as a scheme of force control [3].

The advantage of AFC is the way to eliminate the external disturbance practically. It is practical because the mathematical complexity is reduced significantly since it operates either on the physical measurements of relevant parameters or on the estimated parameters[2]. Besides, the computational burden is much reduced and hence it can be easily implemented in real-time. For the crane system used in the study with reference to the trolley component and from *Newton's* second law of motion:

$$\Sigma F = m.a \tag{15}$$

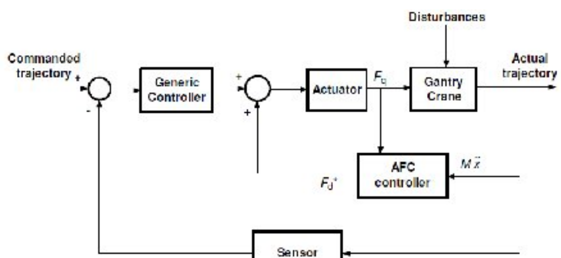


Figure 3: Schematic diagram of a crane model

The commanded trajectory in this study is the desired position of the trolley and sway angle of the payload. The most important equation for the AFC scheme is to obtain the estimated disturbance force in the AFC as seen in figure 3:

$$F_d{*} = F_q - M\ddot{x} \tag{16}$$

## V. Control System Design

The control system design that is built consists of several sensors and actuators which support the proposed methodology, in this case PID and AFC. The sensors used are accelerometer as tilt and acceleration sensor, current sensor used to count the torque, rotary encoder used to count destination and velocity, and the last is weight sensor. The actuator is three DC motor for trolley, hoist, and rope mechanism. The PID formulation is a classic controller typically represented by the following equation:

$$G_c(s) = K_p + K_i Is + K_d s \tag{17}$$

In the program, equation 15 will be translated the following program:

$$PID = Kp.Error + Ki.iError + Kd.dError \tag{18}$$

$$AFC = Force - Actual\ Force \tag{19}$$

$$Force = \frac{ixKtn}{r} \tag{20}$$

$$Actual\ Force = m\ x\ a \tag{21}$$

$$PID = Kp.Error + Ki.iError + Kd.dError + AFC \tag{22}$$

## VI. Result And Discussion

This part will report the result of experiment on the plant based on control system design. The program for controller is in accordance with the proposed control method. This experiment has a purpose to know the robustness of the system. The first experiment is done using PID control by tuning the Kp, Ki, and Kd at first. Then the second experiment is done using AFC. With this experiment, it will be known the characteristic of each controller. For each experiment, the payload that is suspended in the hook is from 0 up to 12 kg with step of 3 kg. So there will be 5 experiments for each method.

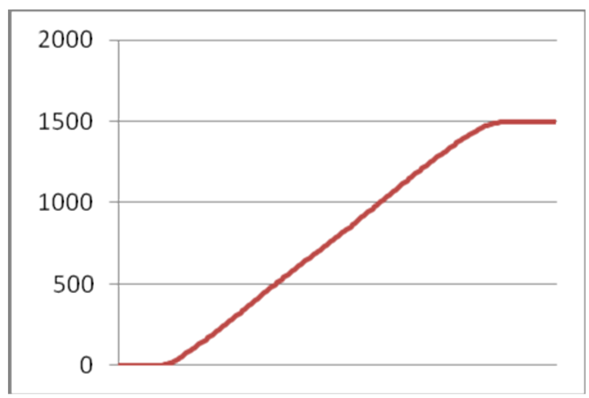


Figure 4: Position vs time with 3 kg load (PID control)

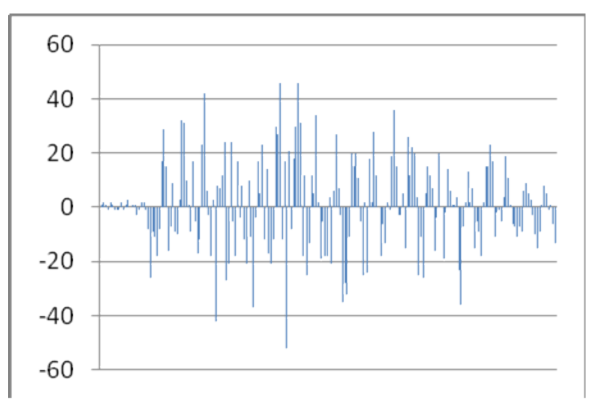


Figure 5: Sway angle vs time with 3 kg load (PID control)

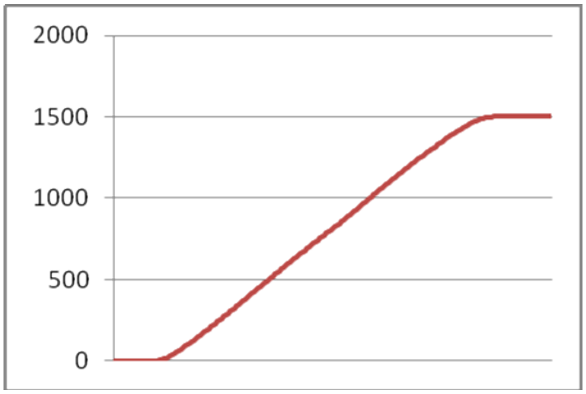

Figure 6: Position vs time with 3 kg load (AFC method)

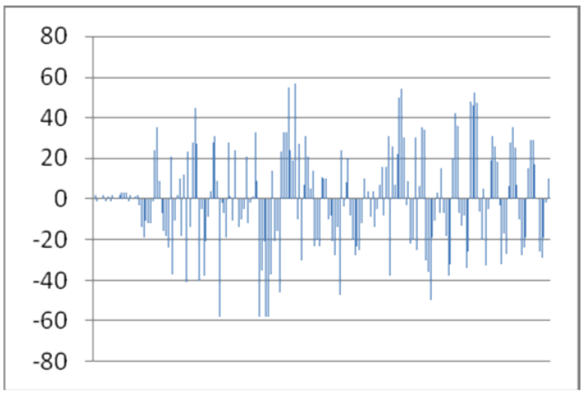

Figure 7: Sway angle vs time with 3 kg load (AFC method)

Table 1: Data experiment of PID and AFC control

| Weight (kg) | Experiment of PID control | | | |
|---|---|---|---|---|
| | Position (pulses) | Swing Angle | | Time (s) |
| | | Start | Stop | |
| 0.5 | 1482 | -17 to 17 | -8 to 8 | 10 |
| 3 | 1487 | -26 to 26 | -15 to 17 | 10 |
| 6 | 1487 | -31 to 26 | -10 to 11 | 10 |
| 9 | 1483 | -31 to 26 | -10 to 11 | 10 |
| 12 | 1477 | -15 to 12 | -27 to 21 | 10 |
| Weight (kg) | Experiment of AFC control | | | |
| | Position (pulses) | Swing Angle | | Time (s) |
| | | Start | Stop | |
| 0.5 | 1497 | -12 to 14 | -5 to 5 | 10 |
| 3 | 1500 | -19 to 24 | -29 to 29 | 10 |
| 6 | 1500 | -12 to 14 | -19 to 20 | 10 |
| 9 | 1498 | -23 to 22 | 24 to 24 | 10 |
| 12 | 1493 | -14 to 13 | -13 to 17 | 10 |

Table 1 is the experiment result of the plant using PID and AFC. The target is 3 meters position. From the table it can be seen that there isn't difference performance of PID control and AFC. When starting, moving, or stop the difference of the swing angle is small enough so that it is difficult to distinguish which performance of each control method is better. The range of data from accelerometer to detect the swing angle for both controllers is almost the same. Time taken to reach the reference position is also the same, 10 seconds. The difference appears at the position reached by both controllers. From 1500 pulses, PID control goes a little farther from the reference position with an average error for each load lifted can be seen in table 5.9. But with the PIDAFC shows better result for each load lifted. Even on some experiments show error of 0 %. Here is the table of error position.

Table 2: Error position

| Weight (kg) | Error of Position (%) | |
|---|---|---|
| | PID Control | AFC |
| 0.5 | 1.2 | 0.2 |
| 3 | 0.8 | 0 |
| 6 | 0.8 | 0 |
| 9 | 1.1 | 0.1 |
| 12 | 1.5 | 0.4 |

## VII. CONCLUSION

A simple method of anti-sway control for haptic crane has been demonstrated. Under various weight of payload to be lifted and operation setting the experiment results show the superiority of performance of the haptic crane system with the AFC method compared to PID control. This clearly implies that the AFC method is very effective and robust control system. With the additional of weight sensor in the hook as the principle of haptic technology the calculation on AFC method even get easier. From the experiment the value of swing angle is almost the same. It is difficult to differentiate the better performance between two control method related to the swing angle. The time required to reach the reference position is the same that is 10 seconds. But the AFC method can achieve a more accurate reference position compared to PID control. This is because for PID, when the trolley will reach the reference position, the pulse to turn motor is not able to move the trolley because it is too small. With PIDAFC, the difference of the actual force of the trolley and motor torque produces an additional pulse to the controller to drive the trolley.

## NOMENCLATURE

| | |
|---|---|
| i | Number of degrees of freedom |
| $F_i$ | Net external forces acting in the direction |
| $q_i$ | Set of generalized co-ordinates, where $i$ = 1,2,3…..n |
| $L$ | System Lagrangian which is comprised of the kinetic and Potential energy |
| $T$ | Total Kinetic energy of the system |
| $U$ | Total Potential energy of the system |
| $m_1$ | Mass of trolley |
| $m_2$ | Mass of payload |
| l | Length of rope |
| g | The gravity acceleration |

| | |
|---|---|
| x | Horizontal position of trolley |
| $\dot{x}$ | The Velocity of the trolley |
| $\ddot{x}$ | The Acceleration of the trolley |
| $\theta$ | The sway angle of payload |
| $\dot{\theta}$ | The speed of swaying of payload |
| $\ddot{\theta}$ | The acceleration of swaying of payload |
| $\ddot{\theta}_{ref}$ | The angular acceleration |
| $K_t$ | The motor torque constan |
| $F_x$ | The force acting on the trolley |
| $F_l$ | The force acting on the hoisting rope |
| $l$ | The length of hoisting rope |
| $\dot{l}$ | The hoisting rope extending speed |
| $\ddot{l}$ | The hoisting rope extending accelerarion |
| *IN* | Moment of inertia |
| $\sum F$ | The total of force |
| M | The mass |
| a | The acceleration |
| $T_d$ | The disturbance torque |
| $T_q$ | The measured actuator torque |
| $T_q$* | The estimated disturbances torques |
| I | current |
| r | radius |
| τ | the torque |
| F | The force |
| $a_x$ | Acceleration of accelerometer of the incline |

## VIII. REFERENCES


[1] Costa, Guiseppe. (1999). "Robust Control for Gantry Cranes". University of New South Wales, Australia: Master of Thesis

[2] Mailah, M. And Yoong, Chia S. (2008). "Disturbance Rejection Control applied to A Gantry Crane".Jurnal Mekanikal. No. 25, 64-79.

[3] Pitowarno, Endra. (2006). "Robotika Desain, Kontrol, dan Kecerdasan Buatan". Yogyakarta: ANDI.

[4] Kim, Yong S., Hong, keum S., and Sul, Seung Ki. (2004). Anti- Sway Control of Container Cranes: Inclinometer, Observer, and State Feedback". International Journal of Control, Automation, and System, vol. 2, no. 4, pp. 435-449.