# Analysis of 3D Gantry Crane System by PID and VSC for Positioning Trolley and Oscillation Reduction

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***Abstract*—Gantry Crane System is a mechanism in heavy engineering that moves payload such as container from one point to another. Generally, an experienced operators or an experts are required to control the gantry position manually while minimizing the payload vibration or swing oscillation. Therefore, those manpower have to be trained in order to operate the gantry crane system safely and efficiently. Thus, in order to overcome this problem, a controller is implemented to the system. This paper presents a controls strategy of Proportional-Integral-Derivative and Variable Structure Control (PID+VSC) in the gantry crane system. The PID controller is used to control the trolley position while the VSC controller is used to control the payload oscillation. The performances are compared to the Proportional-Integral-Derivative and Proportional-Derivative (PID+PD) controller in terms of the precision of trolley position with the minimization of payload oscillation.**

***Index Terms*— Gantry Crane System; PID Controller; Variable Structure Control.**

## I. Introduction

A crane system is used frequently to move the load in factories and harbours. The trolley at the crane is used to move the load to the desired target without causing any undesired oscillation. However, controlling the crane manually by human will tends to excite sway angles of the hoisting line and degrade the overall performance of the system. At a very low speed, the payload angle can be ignored and contrarily for a high speed condition. The sway angle become larger and hard to settle down during movement and unloading. Besides, the effect of increasing the hoisting will causes a degradation on of the sway angle performance. The failure of controlling the system might harmful to people and surroundings [1-3].

Intelligent control algorithms such as fuzzy, sliding mode, neural network and genetic algorithm have a lot of advantages related to the interpolative reasoning approach, but also have some restrictions due to its complexity. Input shaping technique has been proposed for the vibration control [4-6]. However, this method is focused on the payload oscillation compared to the positioning of the trolley. In [7-9], a Fuzzy Logic Controller (FLC) is implemented in the 3D crane system to reduce the oscillations during the movement of a 3D crane system. The research is improved by designing a controller by using bond graph model of the 3D crane system [10]. However, the fuzzy logic designed is struggled in the finding of satisfactory rules, membership function, fuzzification and defuzzification parameter heuristically [11]. On the other hand, feedback controls which are well known to be less sensitive to the parameter variations and the disturbances have also been proposed. From the previous research, it is clearly seen that Proportional-Integral-Derivative (PID) controller was able to control the movement of the trolley to reached to the desired position [12-13]. However, in terms of gantry oscillation, the previous study shown that the Sliding Mode Controller (SMC) which is used the concept of Variable Structure Control (VSC) performs better than PID controller [14-18].

In this paper, the PID and VSC are used to control the positioning of payload without oscillation. The controller is implemented in the simulation platform of 3D INTECO gantry crane system as shown in Figure 1.

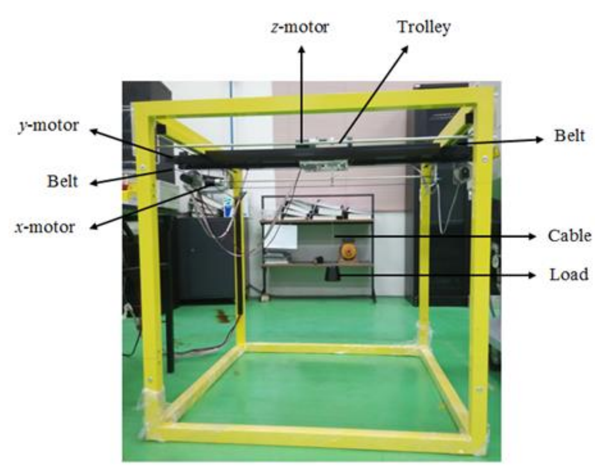


Figure 1: 3D INTECO Crane System

The crane consists of a payload hanging on a cable, wound by a motor mounted on a trolley. The payload is lifted and lowered in the z-direction. The horizontal motion in x-direction are capable for the rail and trolley. Furthermore, the trolley is able to move in horizontal along the rail in the y-direction. There are three DC motors in the system which are used for travelling, traversing and hoisting in x, y and z axes respectively. In this research, the movement in y-direction is been focused. The PID controller is designed in a feed-back structure aims to control the trolley movement in order to achieve the desired position whereas the VSC controller is designed in a feed-forward structure used to minimize the oscillation during the movement. The Performances of the proposed control schemes has been assessed according to the precision of the trolley position and the reduction in the payload oscillation.

## II. 3D CRANE SYSTEM DESCRIPTION

Figure 2 shows the schematic representation of 3D gantry crane system [6], [19]. There are five identical encoders measuring five state variables; $x_w$ represents the distance of the rail with the cart from the center of the construction frame; $y_w$ is the distance of the cart from the center of the rail; R denotes the length of the lift-line; α represents the angle between the y axis and the lift-line; β is the angle between the negative direction on the z-axis and the projection of the lift-line onto the *xz*-plane.

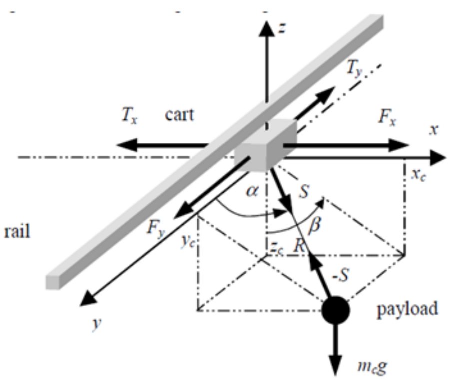


Figure 2: Schematics of 3D gantry crane system

The dynamic equations of motion in y-direction for the gantry crane system is obtained as denoted in Equation (1) and Equation (2) where, $y_t$ is the position of trolley and $y_p$ is the position of payload oscillation [6]. The parameters implemented to the gantry crane system are tabulated in Table 1.

Table 1
Parameters of gantry crane system [6]

| Parameters | Unit | Values |
|---|---|---|
| Payload mass | $m_c$ | 0.46 kg |
| Trolley mass | $m_w$ | 1.155 kg |
| Moving rail mass | $m_s$ | 2.20 kg |
| Gravity | g | 9.81 $ms^{-1}$ |
| Friction force at x-axis | $T_x$ | 100 $Nsm^{-1}$ |
| Friction force at y-axis | $T_y$ | 82 $Nsm^{-1}$ |
| Friction force at z-axis | $T_z$ | 75 $Nsm^{-1}$ |
| Length of cable | R | 0.5 m |

$$\ddot{y}_t = \left(\frac{F_x}{m_w} - \frac{T_x}{m_w}\right) + \left(\frac{m_c}{m_w}\right)\left(\frac{F_z}{m_c} - \frac{T_z}{m_c}\right)\cos\alpha \tag{1}$$

$$\ddot{y}_p = \ddot{y}_t + \left(\ddot{R} - R\dot{\alpha}^2\right)\cos\alpha - \left(2\dot{R}\dot{\alpha} + R\ddot{\alpha}\right)\sin\alpha \tag{2}$$

## III. CONTROL SCHEME

In gantry crane system, there are two control objectives which are needed to be focused: (1) control the trolley to reach the desired position and (2) control the oscillation of the angle which created from the system while moving the load to the desired position. Therefore, in order to control these two control objectives; PID controller (KP, KI and KD) is used to control the trolley position while PD (KPs and KDs) and VSC (K1 and K2) are used to minimize the payload oscillation. The control structure of the system is illustrated in Figure 3.

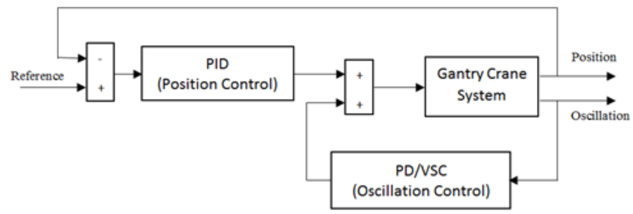


Figure 3: Block diagram of control structure in gantry crane system

### A. Proportional-Integral-Derivative (PID) Controller

PID controller is a control feedback mechanism controller which is widely used in industrial control system. PID controller involves three control terms which are the proportional (P), the integral (I) and the derivative (D). PID controller is used to calculate an error value as the difference between a measured process variable and a desired set point. It is also used to minimize the error by adjusting the process control inputs.

In PID controller, there are three parameters which are needed to be tuned. One of the parameter is proportional gain, $K_P$ in the proportional controller. This gain has the effect of reducing the rise time and steady-state error but the percentage of the overshoot in the system is high. In the PID controller, $K_I$ as the integral gain, which will decreased the rise time but it also eliminating the steady-state error of the system. Even though the error is eliminated, but the percentage of the overshoot is increase and simultaneously affect the settling time. In order to improve the performances of the system, derivative gain, $K_D$ in the derivative controller is introduced. This gain will take action to improve the transient specification and stability of the system.

The equation of PID controller is given by:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt}(t) \tag{3}$$

$$u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int e(t)dt + T_d \frac{de}{dt}(t) \right] \tag{4}$$

In order to achieve a high stability and a short transient response of the system, an appropriate gain value must be obtained from the PID tuning process. It is difficult to adjust and obtain the optimal parameters. Therefore, several tuning methods will be implemented in order to obtain the best parameter of PID controller.

### *B. Variable Structure Control (VSC)*

VSC is a system evolved from the pioneering work in Russia by Emel'yanov and Barbashin in the early 1960s [20-21]. VSC concepts have been subsequently–utilized in the design of robust regulators, model-reference systems, adaptive schemes, tracking systems, state observers and fault detection system.

VSC are a class of systems whereby the control law is deliberately changed during the control process according to some defined rules which depend on the state of the system. For the purpose of illustration, consider the double integrator given by:

$$\ddot{y}(t) = u(t) \tag{5}$$

Initially consider the effect of using the feedback control law:

$$u(t) = -ky(t) \tag{6}$$

where k is strictly positive scalar.

Consider instead the control law:

$$u(t) = \begin{cases} -k_1 y(t) & \text{if } y\dot{y} < 0 \\ -k_2 y(t) & \text{otherwise} \end{cases} \tag{7}$$

where $0 < k_1 < 1 < k_2$ .

The phase plane $(y, \dot{y})$ is partitioned by the switching rule into four quadrants separated by the axes as shown in Figure 4. The control law $u = -k_2 y$ will be effected in the quadrants of the phase labeled (a). In this region, the distance from the origin of the points in the phase portrait decreases along the system trajectory. Likewise, in region (b) when the control law $u = -k_1 y$ is in operation, the distance from the origin of the points in the phase portrait also decreases. The phase portrait for the closed loop system under the variable structure control law $u$ is obtained by splicing together the appropriate regions from the two phase portraits as illustrated in Figure 4. In this way the phase portrait must be spiral in towards the origin and an asymptotically stable motion result as in Figure 5.

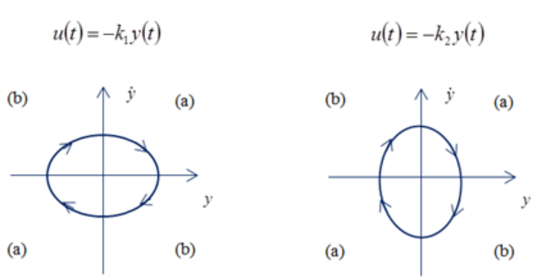


Figure 4: Phase portraits of simple harmonic motion [16]

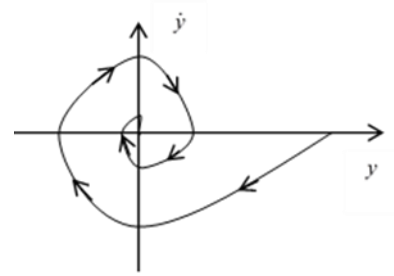


Figure 5: Phase portrait of the system under VCS [16]

## IV. RESULTS AND DISCUSSION

### *A. Parameters of Controllers*

In order to control the trolley reached to the desired position, PID controller has been implemented which contains the variable of $K_P$, $K_I$, and $K_D$. However, in controlling the payload oscillation, two types of controller have been examined which are PD and VSC. The parameters contain in PD are $K_{Ps}$ and $K_{Ds}$ whereas the parameters of VSC controller are $K_1$ and $K_2$. The parameters of PID+PD and PID+VSC are tuned by using Particle Swarm Optimization (PSO). All of the parameters are tabulated in Table 2.

Table 2
Parameters of controllers

| PID+PD | | PID+VSC | |
|---|---|---|---|
| Parameters | Value | Parameters | Value |
| $K_P$ | 20.9716 | $K_P$ | 5.0000 |
| $K_I$ | 10.8455 | $K_I$ | 2.0000 |
| $K_D$ | 4.4700 | $K_D$ | 0.5000 |
| $K_{Ps}$ | 4.9952 | $K_1$ | -0.8000 |
| $K_{Ds}$ | 0.0714 | $K_2$ | -7.0000 |

### *B. Trolley Position*

Figure 6 shows the trolley position in the gantry crane system which controlled by the PID controller. Based on the response of the gantry crane system, the percentage overshoot created by the PID+VSC is larger with the differences of 5.27% compared to the PID+PD. Even though the percentage of overshoot is differ, but with the implementation of PID+VSC, the trolley is able to reached to the desired position of 0.3 m precisely compared to the PID+PD which is only reached at 0.2999 m since the steady state error of the PID+PD controller is 0.0001 m and PID+VSC did not have any of steady state error. The performance of the trolley positioning is tabulated in Table 3.

Table 3
Performance of desired position

| Tuning Method | Performance | | |
|---|---|---|---|
| | OS (%) | $T_s$ (s) | SSE (m) |
| PID+PD | 11.40 | 4.11 | 0.0001 |
| PID+VSC | 16.67 | 8.30 | 0.0000 |

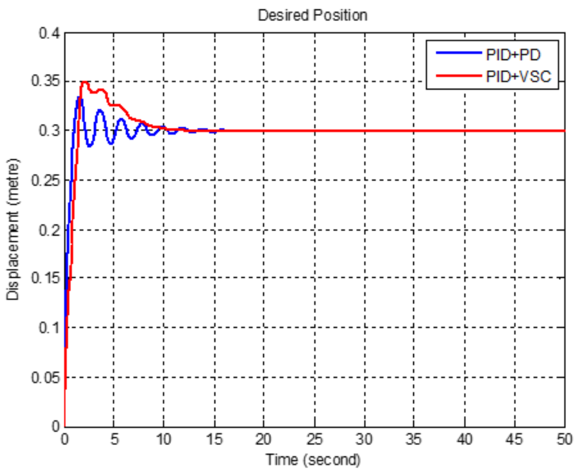


Figure 6: Response of desired position

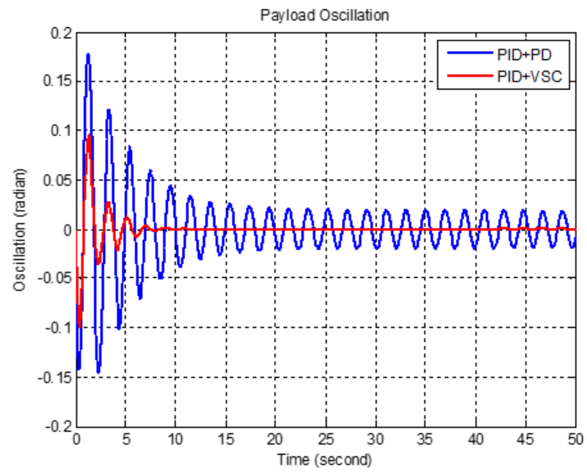


Figure 7: Response of payload oscillation

### *C. Payload Oscillation*

Figure 7 shows the payload oscillation in the gantry crane system which is controlled by the PD and VSC controller to minimize the oscillation while handling the load. It shows that the maximum payload oscillation created from PD controller is 0.1777 rad at 1.27 s. The maximum oscillation created from VSC controller is 0.0088 rad which is smaller than the oscillation created from the PD controller. Besides that, the oscillation is minimized and stop oscillated which produce zero error. Figure 7 shows the payload oscillation in the gantry crane system which is controlled by the PD and VSC controller to minimize the oscillation while handling the load. It shows that the maximum payload oscillation created from PD controller is 0.1777 rad at 1.27 s. The maximum oscillation created from VSC controller is 0.0088 rad which is smaller than the oscillation created from the PD controller. Besides that, the oscillation is minimized and stop oscillated which produce zero error.

Table 4
Performance of payload oscillation

| Tuning Method | Performance | | |
|---|---|---|---|
| | Max oscillation, $\theta_{max}$ (radian) | Time, $T$(s) | Error peak to peak (radian) |
| PID+PD | 0.1777 | 1.27 | $3.72\times10^{-2}$ |
| PID+VSC | 0.0988 | 0.40 | $3.84\times10^{-5}$ |

Figure 8 below shows the phase portraits created from the payload oscillation of the gantry crane system. The point started at the origin as the state of the initial of the load. After the load has been moved to the desired position, the load started to swing in negative x-axis to positive x-axis until the load reached at the desired position and the oscillation began to decrease and stop which it back to the origin.

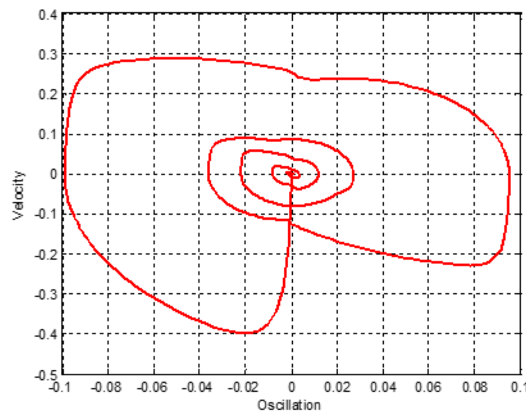


Figure 8: Phase portrait of VSC

## V. CONCLUSION

This paper has presented the design of an optimal PID+VSC controller for a gantry crane system. The Dynamic mathematical model of the motion in 3D INTECO gantry crane system has been derived. Simulation results shown that PID+VSC controller is effectively move the trolley as fast as possible with low payload oscillation compared to PID+PD controller. In addition, the system is not only achieved the positioning target but also improve the safety. In future work, a new controller can be introduce and implement in the system for more effective performance.

## ACKNOWLEDGMENT

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