Journal of Engineering Science and Technology
Special Issue on ISSC'2016, April (2017) 26 - 38

DISTURBANCE REJECTION EXPERIMENTAL IN 3D INTECO GANTRY CRANE SYSTEM VIA PID-VSC TUNED BY PFPSO

SHARIFAH YUSLINDA SYED HUSSIEN, ROZAIMI GHAZALI*,
HAZRIQ IZZUAN JAAFAR, CHONG CHEE SOON

Centre for Robotics and Industrial Automation,
Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
*Corresponding Author: rozaimi.ghazali@utem.edu.my

Abstract

Gantry Crane System (GCS) is a mechanism in heavy engineering that moves payload from one point to another. Commonly, an experienced operator is required to control the trolley position manually while minimizing the payload oscillation. The transferring process should be done with careful and concentration to ensure the safety environment. Thus, in order to ensure the safety condition, a control strategy of Proportional-Integral-Derivative and Variable Structure Control (PID-VSC) is implemented in the 3D INTECO GCS. The Proportional-Integral-Derivative (PID) controller is used to control the trolley position while the Variable Structure Control (VSC) is used to control the payload oscillation. The parameters of the controllers are defined by Priority-based Fitness Particle Swarm Optimization (PFPSO). The performances are compared to the Proportional-Integral-Derivative and Proportional-Derivative (PID-PD) controller tuned by PFPSO in terms of the precision of trolley position with the minimization of payload oscillation. The robustness of the controller is verified by the injection of internal disturbance in gantry crane system. With the proposed controller, the experimental of 3D INTECO GCS shows that the system is capable of minimizing the payload oscillation while achieving satisfactory trolley position tracking.

Keywords: 3D INTECO gantry crane system, Proportional-integral-derivative controller, Variable structure control, Priority-based fitness particle swarm optimization.

1. Introduction

Gantry Crane System (GCS) 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

Nomenclatures

c_1, c_2	Acceleration coefficient
e_{ss}	Steady state error, meter
F_x	Force driving rail with trolley, Nsm^{-1}
F_y	Force driving trolley along rail, Nsm^{-1}
g	Gravity, ms^{-1}
m_c	Mass of payload, kg
m_s	Mass of moving rail, kg
m_w	Mass of trolley, kg
N_P	Number of particle
N_I	Number of iteration
OS	Overshoot, %
R	Cable length, meter
r_1, r_2	Random numbers
T_s	Settling time, second
y_c	Payload oscillation in y-axis
y_w	Trolley position in y-axis

Greek Symbols

α	Angle of payload oscillation, radian
α_{max}	Maximum angle of payload oscillation, radian
ω	Inertia weight factor

Abbreviations

FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
GCS	Gantry Crane System
PFBPSO	Priority-based Fitness Binary Particle Swarm Optimization
PFFA	Priority-based Fitness Firefly Algorithm
PFPSO	Priority-based Fitness in Particle Swarm Optimization
PFS	Priority-based Fitness Scheme
PID	Proportional-Integral-Derivative
PID-PD	Proportional-Integral-Derivative and Proportional-Derivative
PID-VSC	Proportional-Integral-Derivative and Variable Structure Control
SMC	Sliding Mode Controller
VSC	Variable Structure Control
ZN	Zeigler-Nichols

manually by human will tends to excite sway angles of the hoisting line and degrade the overall performance of the system.

There are many techniques have been proposed and implemented in GCS by previous researchers such as input shaping, Fuzzy Logic Controller (FLC), Proportional-Integral-Derivative (PID), Sliding Mode Controller (SMC) and others. Input shaping technique has been proposed for the vibration control [1-3]. However, this method is focused on the payload oscillation compared to the positioning of the trolley. In [4-6], FLC is implemented in the 3D GCS to reduce the oscillations during the movement. The research is improved by designing a controller by using bond graph model of the 3D GCS [7]. However, the fuzzy logic designed is struggled in the finding of satisfactory rules, membership function, fuzzification and defuzzification parameter heuristically. 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 PID controller was able to control the movement of the trolley to reach the desired position [8]. However, in terms of payload oscillation, the previous study shown that the SMC which is used the concept idea of Variable Structure Control (VSC) performs better than PID controller [9-12].

Various of control techniques implemented in GCS in order to control the trolley position and payload oscillation. However, there are difficulties in obtaining the optimal parameters for the controller. Therefore, in order to overcome the problem, an optimization of heuristic method and meta-heuristic method had been introduced. Heuristic method such as trial and error is an easiest way to tune the controller but it is not significant and satisfactory performances is not guaranteed. Another tuning method is Ziegler-Nichols (ZN) that is widely used due to their simplicity. Unfortunately, it is found that this tuning method is very aggressive and leads to a large overshoot and oscillatory response.

Nowadays, meta-heuristic method is implemented to obtain a better PID parameters in the GCS. Genetic Algorithm (GA) has been applied to tune PID controller for finding optimal automatic gantry crane [13]. Other than that, Particle Swarm Optimization (PSO) is also utilized as a technique for researching for an optimal PID parameters. Priority Fitness Scheme (PFS) is introduced by Jaafar in 2012 as the combination of PFS and optimization. This method is developed to set any of the transient response characteristics (settling time (T_s), overshoot (OS) or steady-state error (e_{ss})) based on the priority issue of the system. Priority-based Fitness Particle Swarm Optimization (PFPSO) is a combination of the PFS and PSO which have been implemented in GCS [14-16]. Other than that, these combination has been transform in the binary number which known as Priority-based Fitness Binary Particle Swarm Optimization (PBPSO) [17]. Besides, Priority-based Fitness Firefly Algorithm (PFFA) to obtain the optimal parameters of PID controller in order to achieve a satisfactory performance [18].

This paper presents the development of control scheme experimentally for 3D INTECO GCS of Proportional-Integral-Derivative and Variable Structure Control (PID-VSC) which focusing in *y*-direction movement. The PID controller is designed to control the trolley movement in order to achieve the desired position whereas the VSC controller is designed to minimize the oscillation during the movement. The parameters of the controller are optimized by PFPSO. The performances of the proposed control schemes has been compared to Proportional-Integral-Derivative and Proportional-Derivative (PID-PD) tuned by PFPSO according to the precision of the trolley position and the reduction in the payload oscillation. The robustness of the controller is examined by the injection of the internal disturbance in 3D INTECO GCS.

2. D INTECO Gantry Crane System

The 3D INTECO GCS and the schematic diagram are shown in Figs. 1 and 2. There are five identical encoders measuring five state variables; x_w represents the distance of the rail with the trolley from the centre of the construction frame; y_w is the distance of the trolley from the centre 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.

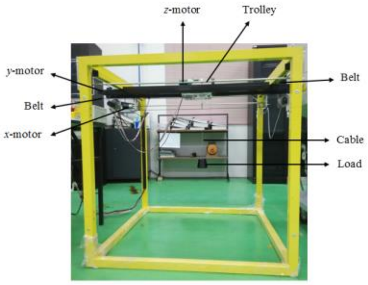

Fig. 1. 3D INTECO GCS.

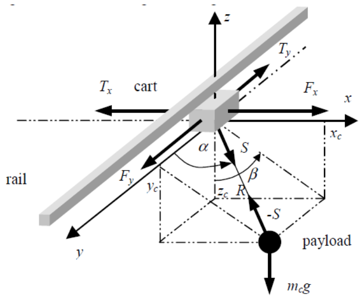

Fig. 2. Schematics of 3D INTECO GCS.

The dynamic equations of motion in y-direction in for the GCS is obtained as denoted in Eqs. (1) and (2) where, y_w is the position of trolley and y_c is the position of payload oscillation [6]. The specifications of the model of GCS are shown in Table 1.

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

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

Table 1. Parameters of 3D INTECO GCS.

Parameters	**Unit**	**Values**
Payload mass	m_c	0.4600 kg
Trolley mass	m_w	1.1550 kg
Moving rail mass	m_s	2.2000 kg
Gravity	g	9.8100 ms^{-1}
Friction force at *x*-axis	T_x	100.0000 Nsm^{-1}
Friction force at *y*-axis	T_y	82.0000 Nsm^{-1}
Friction force at *z*-axis	T_z	75.0000 Nsm^{-1}
Length of cable	R	0.3000 m

3. Control Strategy

In 3D INTECO GCS, there are two control objectives which are needed to be focused which are controlling the trolley to reach the desired position and controlling the payload oscillation which created from the system while moving the load to the desired position. Therefore, in order to control these two control objectives; PID controller is used to control the trolley position while PD and VSC are used to minimize the payload oscillation. All the controllers are optimized by PFPSO in order to obtain the optimal parameters. The control structure of the system is illustrated in Fig. 3.

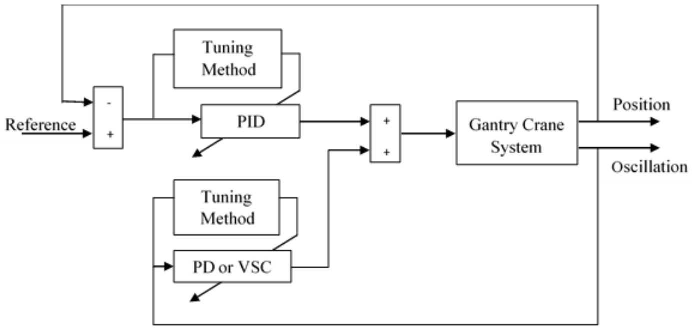

Fig. 3. Block diagram of control structure in GCS.

3.1. Proportional-Integral-Derivative controller

Proportional-Integral-Derivative (PID) controller is a control feedback mechanism controller which is widely used in industrial control system. 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 Eq. (3).

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de}{dt}(t) \tag{3}$$

3.2. Variable structure control

Variable Structure Control (VSC) is a system evolved from the pioneering work in Russia by Emel'yanov and Barbashin in the early 1960s [19]. 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:

$$\ddot{y}(t) = u(t) \tag{4}$$

Initially consider the effect of using the feedback control law:

$$u(t) = -ky(t) \tag{5}$$

where k is strictly positive scalar.

Consider instead the control law:

$$u(t) = \begin{cases} -k_1 y(t) & \text{if } y\dot{y} < 0 \\ -k_2 y(t) & \text{otherwise} \end{cases} \tag{6}$$

where $0 < k_1 < 1 < k_2$.

The phase plane (y, ẏ) is partitioned by the switching rule into four quadrants separated by the axes as shown in Fig. 4. The control law $u = -k_2 y$ will be effected in the quadrants of the phase labelled (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 $-k_1\ y$ 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 Fig. 4. In this way, the phase portrait must be spiral in towards the origin and an asymptotically stable motion result as in Fig. 5.

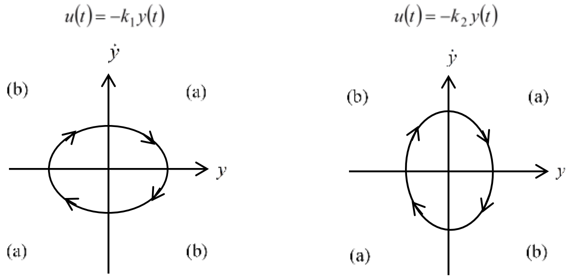

Fig. 4. Phase portraits of simple harmonic motion [20].

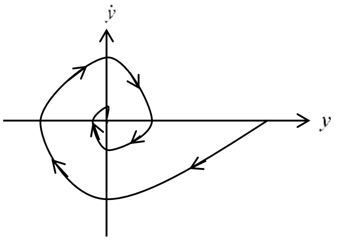

Fig. 5. Phase portrait of the system under VCS [20].

3.3. Priority-based fitness particle swarm optimization

Particle Swarm Optimization (PSO) is a meta-heuristic global optimization method which introduced by James Kennedy and Russell Eberhart in 1995 [21]. PSO was developed from the swarm intelligence and based of bird and fish flock movement behaviour to find the food. In order to find the food, a group of birds will move together in a group to find food from one place to another. They can smell and know the food well if it is enough for them or not.

The basic principle of the PSO algorithm is it uses a number of particles (agents) that constitute a swarm moving around in the search space looking for the best solution. Each of the particles is treated as appoint in N-dimensional space which adjusts its flying according to its own flying experiences of other particles. Each particle keeps track of its coordinates in the solution space which are associated with the best solution (fitness) that has achieved does far by that particle. This value is known as personal best, P_{BEST}. Another best value that is tracked by the PSO is the best value obtained so far by any particle in the neighbourhood of that particle which known as global best, G_{BEST}. Each particle can be shown by its current velocity and position as shown in Eqs. (7) and (8). The initialization value in PSO is tabulated in Table 2.

$$v^{i+1} = \omega v^{i} + c_1 r_1 \left(P_{BEST} - x^{i}\right) + c_2 r_2 \left(G_{BEST} - x^{i}\right) \tag{7}$$

$$x^{i+1} = x^{i} + v^{i+1} \tag{8}$$

Table 2. Initialization value in PSO.

Number of particle,	N_P	20
Number of iteration	N_I	100
Search range	-	0 to 20
Acceleration coefficients	c_1, c_2	2
Random numbers	r_1, r_2	0 to 1
Inertia weight factor	ω	0.9 and linearly decreased to 0.4 at some stage of iteration

Priority-based Fitness Particle Swam Optimization (PFPSO) is implemented as the PID and VSC controllers tuning method in order to obtain the parameters. The value P_{BEST} and G_{BEST} are updated according to the priority: OS, T_s and e_{ss} which means that overshoot, OS is set as highest priority, followed by settling time, T_s and steady-state error, e_{ss}. The process of the PFPSO are shown in Figs. 6 and 7.

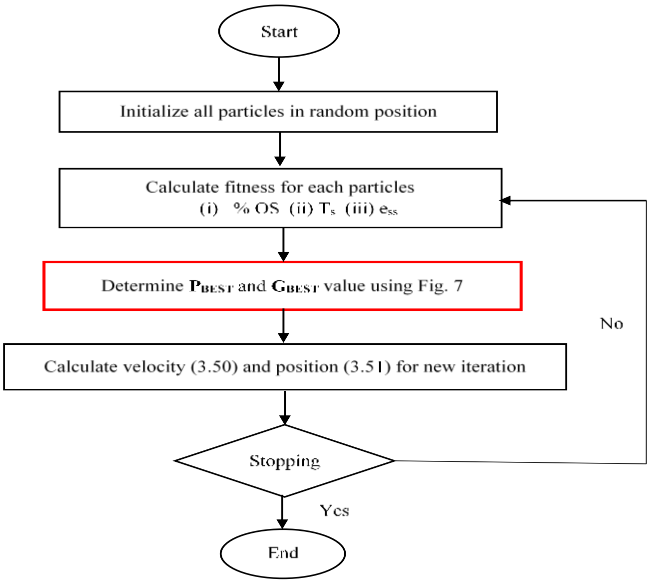

Fig. 6. General process of PFPSO [15].

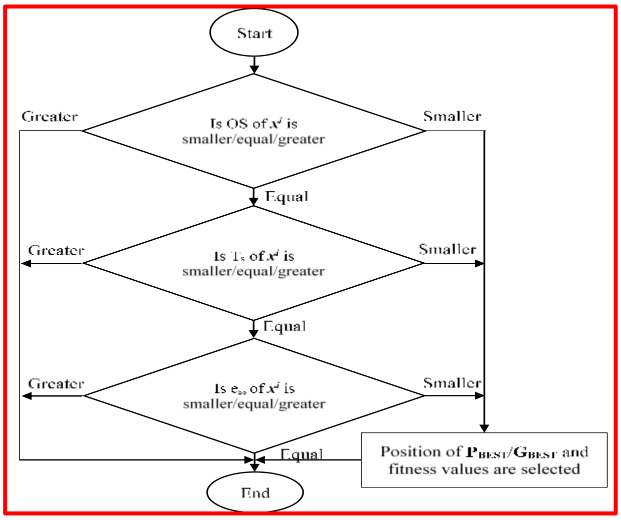

Fig. 7. Process of PFPSO according to the priority [15].

4. Results and Discussion

In this paper, PID-VSC controller is implemented in 3D INTECO GCS in order to control the position of trolley and minimize the oscillation of payload. The parameters of PID-VSC controller is optimized by PFPSO. The performances of GCS is verified in terms of trolley position and payload oscillation. The internal disturbance rejection is examined to examine the robustness of the controller weather the controller is able to withstand the disturbance or not. In this paper, a combination of several step which represent the disturbance such as wind is simulated in MATLAB. The internal disturbance is injected in the GSC at 80.0000 seconds to 100.0000 seconds.

4.1. Parameters of controllers

In Fig. 8, the *y* reference for the trolley is set to 0.3000 meter as located in the middle of the rail of *y*-axis. The position of the trolley is controlled by PID controller ($\boldsymbol{K_P}$, $\boldsymbol{K_I}$ and $\boldsymbol{K_D}$) whereas the payload oscillation is controlled by PD controller ($\boldsymbol{K_{Ps}}$ and $\boldsymbol{K_{Ds}}$) and VSC controller ($\boldsymbol{k_1}$ and $\boldsymbol{k_2}$).

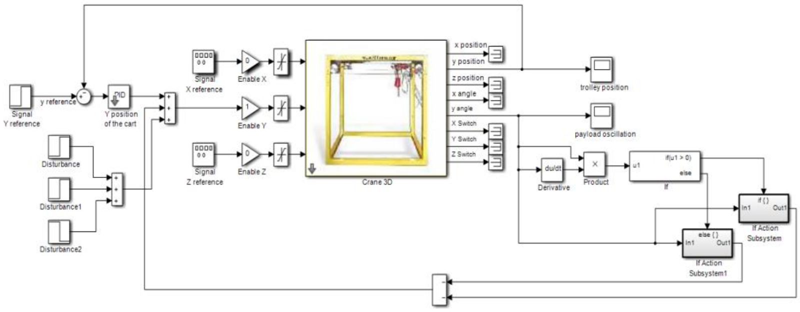

Fig. 8. PID and VSC controllers block diagram in 3D INTECO GCS.

The parameters of $\boldsymbol{K_P}$, $\boldsymbol{K_I}$, $\boldsymbol{K_D}$, $\boldsymbol{K_{Ps}}$, $\boldsymbol{K_{Ds}}$, $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ are tuned by PFPSO in order to obtain the optimal value as tabulated in Table 3. The comparison performance of GCS controlled by PID-PD controller and PID-VSC controller is evaluated in terms of trolley position and payload oscillation.

Table 3. Parameters of PID-PD and PID-VSC controllers.

Parameters	PFPSO	Parameters	PFPSO
K_P	2.5224	K_P	3.8625
K_I	0.1076	K_I	0.0025
K_D	3.0353	K_D	1.9258
K_{Ps}	2.9549	k_1	0.6991
K_{Ds}	0.0619	k_2	9.6320

4.2. Trolley position

The trolley position in the GCS which controlled by the PID controller shown in Fig. 9. In the experiment results, the performance of GCS implemented by PID-VSC controller tuned by PFPSO did not created any overshoot and the system reached stable condition at 7.9500 seconds compared to PID-PD controller tuned by PFPSO which took 12.0200 seconds to reach the stable condition. After the disturbance injection at 80.0000 seconds in the system, the time taken for the system to settle was different according to the controller. The system with VSC controller takes 148.7000 seconds to achieve the target position which was 0.3000 meter and it was the fastest arrival time compared to the system which controlled by PD controller which is 192.0000 seconds.

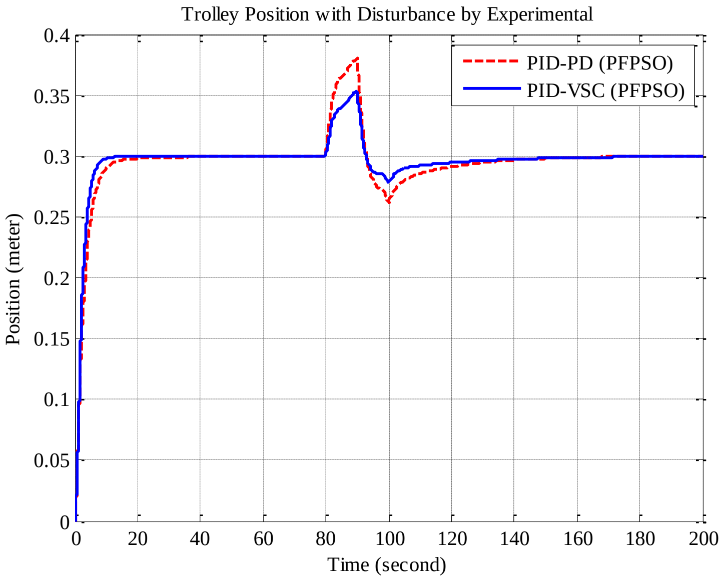

Fig. 9. Trolley position with disturbance by experiment.

The performances of trolley position with disturbance rejection in GCS is tabulated in Table 4. Even though PID-PD controller and PID-VSC controller able to achieve the desired position after the injection of disturbance but PID-VSC controller clearly shown smaller overshoot and e_{ss} than PID-PD controller.

Table 4. Performances of trolley position with disturbance by experiment.

Tuning Methods	Before Disturbance			After Disturbance		
	OS (%)	T_s (second)	e_{ss} (meter) ($\times10^{-3}$)	OS (%)	T_s (second)	e_{ss} (meter) ($\times10^{-3}$)
PID-PD (PFPSO)	0.0000	12.0200	0.1205	26.6947	148.7000	0.3282
PID-VSC (PFPSO)	0.0000	7.9500	0.1079	17.5663	192.0000	0.1892

4.3. Payload oscillation

Figure 10 shows the payload oscillation in the GCS which controlled by the PD controller and VSC controller. It shows that the maximum payload oscillation created from VSC controller is smaller than the maximum payload oscillation from PD controller which is 0.0322 radian at 0.7000 second. The oscillation is slow down towards zero radian at 8.4600 seconds which faster than PD controller. After an injection of step disturbance at 80.0000 seconds, both system started to oscillate. PD controller shown a maximum oscillation of 0.0105 radian at 91.4600 seconds which is higher compared to VSC controller which the maximum oscillation was 0.0079 radian at 90.4000 seconds. PID-VSC controller stopped oscillating at 102.7000 seconds which is faster than PID-PD controller.

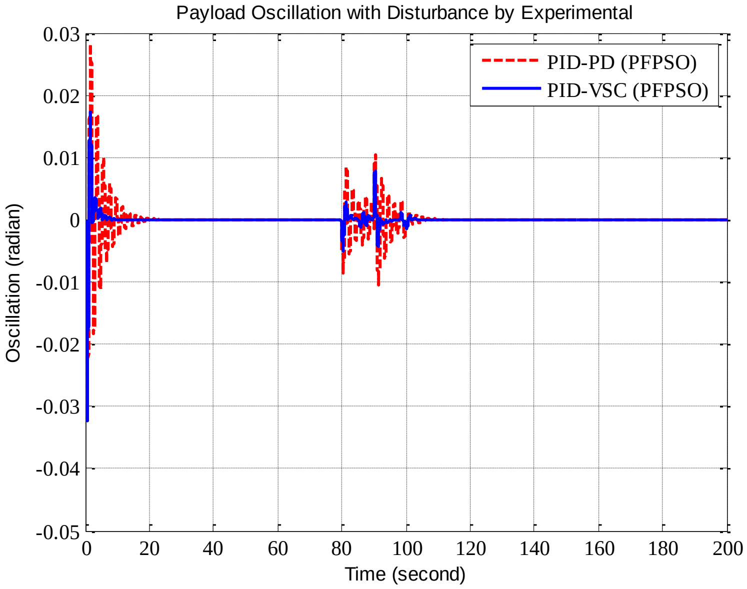

Fig. 10. Payload oscillation with disturbance by experiment.

The performances of payload oscillation with disturbance rejection is tabulated in Table 5. Even though PID-PD controller and PID-VSC controller are able to reject disturbance occurred in GCS, but PID-VSC controller shown the smaller payload oscillation and smaller time taken for payload stopped oscillating after disturbance than PID-PD controller.

Table 5. Performances of payload oscillation with disturbance by experiment.

Tuning methods	**Before disturbance**		**After disturbance**	
	α_{max} (radian)	T_s (second)	α_{max} (radian)	T_s (second)
PID-PD (PFPSO)	0.0294	22.7700	0.0105	113.9000
PID-VSC (PFPSO)	0.0322	8.4600	0.0079	102.7000

5. Conclusions

This paper has presented the design of an optimal PID-VSC controller for a GCS. The dynamic mathematical model of the motion in 3D INTECO GCS has been derived. Experimental results shown that PID-VSC controller tuned by PFPSO is effectively move the trolley as fast as possible with low payload oscillation compared to PID-PD controller tuned by PFPSO. In addition, PID-VSC controller tuned by PFPSO is a robust controller because the proposed controller able to achieve satisfactory performances when a disturbance occurred in the system. Thus, the GCS is not only archive the target position but also improve the safety environment. In future work, a new controller can be introduce and implement in GCS for an effectiveness performance.

Acknowledgement

The authors would like to thank the Ministry of Education (MOE), Centre for Research and Innovation Management (CRIM) and Universiti Teknikal Malaysia Melaka (UTeM) for sponsoring this project. This project is funded by the Fundamental Research Grant Scheme (FRGS) Grant No. FRGS/1/2014/TK03/FKE/F00213.

References

1. Maghsoudi, M.J.; Mohammed, Z.; Pratiwi, A.F.; Ahmad, N.; and Husain, A. R. (2012). An experiment for position and sway control of a 3D gantry crane. *Proceedings of the Fourth IEEE International Conference on Intelligent and Advanced Systems: A Conference of World Engineering, Science and Technology Congress*. Kuala Lumpur, Malaysia, 497–502.
2. Ajayan, M.; and Nishad, P.N. (2014). Vibration control of 3D gantry crane with precise positioning in two dimensions. *Proceedings of the Annual International Conference on Emerging Research Areas: Magnetics, Machines and Drives*. Kerala, India, 1–5.
3. Maghsoudi, M.J.; Mohamed, Z.; Husain, A.R.; and Jaafar, H.I. (2014). Improved input shaping technique for a nonlinear system. *Proceedings of the Fourth IEEE International Conference on Control System, Computing and Engineering*. Penang, Malaysia, 261–266.

4. Wahyudi; and Jalani, J. (2005). Design and implementation of fuzzy logic controller for intelligent gantry crane system. *Proceedings of the Second International Conference on Mechatronics.* Kuala Lumpur, Malaysia, 345–351.
5. Wahyudi; and Jalani, J. (2006). Robust fuzzy logic controller for an intelligent gantry crane system. *Proceedings of the First International Conference on Industrial and Information Systems*. Sri Lanka, 497–502.
6. Antic, D; Jovanovic, Z.; Peric, S.; Nikolic, S.; Milojkovic, M.; and Milosevic, M. (2012). Anti-swing fuzzy controller applied in a 3D crane system. *Engineering, Technology and Applied Science Research*, 2(2), 196–200.
7. Trajkovic, D.M.; Antic, D.S.; Nikolic, S.S.; Peric, S.L.; and Milovanovic, M.B. (2013). Fuzzy logic-based control of three-dimensional crane system. *Automatic Control and Robotics*, 12(1), 31–42.
8. Solihin, M.I.; Wahyudi; Legowo, A.; and Akmeliawati, R. (2009). Robust PID anti-swing control of automatic gantry crane based on kharitonov’s stability. *Proceedings of the Fourth IEEE Conference on Industrial Electronics and Applications*. Xian, China, 275–280.
9. Majid, M.A.; Ibrahim, W.S.W.; Mohamad, S.; and Bakar, Z.A. (2013). A comparison of PID and PD controller with input shaping technique for 3D gantry crane. *Proceedings of the IEEE Conference on System, Process and Control*. Kuala Lumpur, Malaysia, 144-148.
10. Gao, W.; and Hung, J.C. (1993). Variable structure control of nonlinear systems: A new approach. *IEEE Transactions on Industrial Electronics*, 40(1), 45–55.
11. Wilfred, K.J.N.; Sreeraj, S.; Vijay, B.; and Bagyaveeraswaran, V. (2014). Container crane control using sliding mode control. *International Journal of Engineering Research and Technology*, 3(6), 1769–1773.
12. Chang, C.Y.; Hsu, K.C.; Chiang, K.H.; and Huang, G.E. (2008). Modified fuzzy variable structure control method to the crane system with control deadzone problem. *Journal of Vibration and Control*, 14(7), 953–969.
13. Solihin, M.I.; Wahyudi; Kamal, M.A.S.; and Legowo, A. (2008). Objective function selection of GA-based PID control optimization for automatic gantry crane. *Proceedings of the International Conference on Computer and Communication Engineering: Global Links for Human Development*. Kuala Lumpur, Malaysia, 883–887.
14. Jaafar, H.I.; Mohamed, Z.; Abidin, A.F.Z.; and Ghani, Z.A. (2012). PSO-tuned PID controller for a nonlinear gantry crane system. *Proceedings of the Second IEEE International Conference on Control System, Computing and Engineering*. Penang, Malaysia, 515–519.
15. Jaafar, H.I.; Hussien, S.Y.S.; and Ghazali, R. (2015). Optimal tuning of PID+PD controller by PFS for gantry crane system. *10th Asian Control Conference: Emerging Control Techniques for a Sustainable World.* Kota Kinabalu, Sabah, 1–6.
16. Jaafar, H.I.; Ali, N.M.; Mohamed, Z.; Selamat, N.A.; Abidin, A.F.Z.; Jamian, J.J.; and Kassim, A.M. (2013). Optimal performance of a nonlinear gantry crane system via priority-based fitness scheme in binary PSO algorithm. *IOP Conference Series: Materials Science and Engineering*, 53, 012011.

17. Jaafar, H.I.; Mohamed, Z.; Abidin, A.F.Z.; Md Sani, Z.; Jamian, J.J.; and Kassim, A.M. (2014). Performance analysis for a gantry crane system (GCS) using priority-based fitness scheme in binary particle swarm optimization. *Advanced Materials Research*, 903, 285–290.
18. Jaafar, H.I.; Latif, N.A.; Kassim, A.M.; Abidin, A.F.Z.; Hussien, S.Y.S.; and Aras, M.S.M. (2015). Motion control of nonlinear gantry crane system via priority-based fitness scheme in firefly algorithm. *AIP Conference Proceedings*, 1660, 070031.
19. Ghazali, R.; Sam, Y.M.; Rahmat, M.F.; Hashim, A.W.I.M.; and Zulfatman. (2011). Performance comparison between sliding mode control with PID sliding surface and PID controller for an electro-hydraulic positioning system. *International Journal on Advanced Science, Engineering and Information Technology*, 1(4), 447–452.
20. Edwards, C.; and Sarah, K.S. (1998). *Sliding mode controller: Theory and applications*. London: Taylor and Francis Ltd.
21. Kennedy, J.; and Eberhart, R. (1995). Particle swarm optimization. *Proceedings of IEEE International Conference on Neural Networks*. Perth, Australia, 1942–1948.