ANALYSIS OF OPTIMAL MOTION PERFORMANCE FOR UNDERACTUATED GANTRY CRANE SYSTEM USING MOPSO WITH LINEAR WEIGHT SUMMATION APPROACH

H.I.Jaafar[1*], S. Y. S. Hussien[1], R. Ghazali[1], Z. Mohamed[2], J. J. Jamian[2], M. S. M. Aras[1], M. N. M. Nasir[1], M. F. Sulaiman[1]

[1]Center of Robotics and Industrial Automation (CeRIA),
Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka,
76100 Durian Tunggal, Melaka, Malaysia

[2]Faculty of Electrical Engineering, Universiti Teknologi Malaysia,
81310 Skudai, Johor, Malaysia

ABSTRACT

This paper present the development of Multi-Objective Particle Swarm Optimization (MOPSO) with Linear Weight Summation (LWS) approach to enhance the effectiveness and efficiency of Gantry Crane System (GCS). The purpose of using LWS is to control the desired trolley position and payload oscillation according to the Settling Time (Ts), Steady State Error (SSE) and Overshoot (OS). The effectiveness of variation in weight summation is observed to find the optimal motion performances of the system. It demonstrated that GCS is able to achieve the goals while able to move the trolley as fast as possible to the desired position with low payload oscillation. Through this approach, the best optimal motion performances can be achieved by setting similar value of weightage for OS and Ts and reduce the priority for SSE.

KEYWORDS: *Gantry crane system; multi-objective particle swarm optimization; linear weight summation; swarm intelligence*

1.0 INTRODUCTION

Advanced manufacturing technology made Gantry Crane System (GCS) one of the suitable heavy machinery transporters and frequently employed in handling huge materials. It is desirable to move the trolley to a required position as fast as possible with low payload oscillation. However, the crane acceleration required for motion, always induces undesirable load swing (Butler et al., 1991). At higher speed, these sway angles become larger and significant, and caused the payload hard to

* Corresponding author email: hazriq@utem.edu.my

settle down during the unloading process. This frequent unavoidable load swing caused an efficiency drop, load damages and even accidents. To attain positional accuracy of the GCS, a control mechanism that accounts for positioning of the trolley and oscillation of the payload is required.

Several control techniques have been proposed previously for controlling the GCS. In industrial control system, Proportional-Integral-Derivative (PID) control schemes based on the classical control theory have been widely used for a long time (Astrom et al., 2006). Traditional tuning method such as trial and error is generally an easy way to tune the PID controller. However, it is difficult to determine optimal PID gain parameters and thus satisfactory performances cannot be guaranteed. A well-known tuning method is Zigler-Nichols and still widely used due to its simplicity. Unfortunately, the way to find the parameters is very aggressive and leads to a large overshoot and oscillatory responses. Due to the difficulties in finding the optimal value of PID parameters, meta-heuristic methods are implemented in finding the most appropriate value.

Several investigations have been conducted to optimize PID parameters especially based on intelligent techniques. For instance, Genetic Algorithm (GA) has been applied to tune PID for automatic gantry crane (Solihinet et al., 2008a). Furthermore, Artificial Bee Colony (ABC) algorithm is introduced to tune the PID controller. It was employed to tune for higher order plant and the results show that overshoot and settling time can be improved (Abachizadehet et al., 2010). In addition, Ant Colony Algorithm (ACA) was proposed to optimize the parameter of the controller in designing of a nonlinear PID controller. It has flexible and adaptive characteristic in order to find the PID parameters. A satisfactory overall performance of the system has been demonstrated with the controller (Jiajia et al., 2011). Another optimization technique that can be utilized for finding optimal PID parameters is Firefly Algorithm (FA). It has been tested where FA is more powerful and shows superior performances compared to GA for PID controller parameter tuning of the considered nonlinear control system (Roeva et al., 2012). Besides that, Particle Swarm Optimization (PSO) is also investigated for obtaining PID parameters for GCS and it is well known for simple optimization compared to the other optimization methods (Solihinet et al., 2008b; Jaafaret et al., 2012).

2.0 MODEL OF A GANTRY CRANE SYSTEM

Figure 1 show a schematic diagram of a GCS considered in this work. The parameters of m_1, m_2, l, x, Θ, T and F are payload mass, trolley mass, cable length, horizontal position of trolley, swing angle, torque and driving force respectively. GCS is modeled based on (Solihinet et al., 2008b). Some assumptions have been made to minimize the difficulties of modeling such as cable of trolley and hanged load are assumed to be rigid and massless.

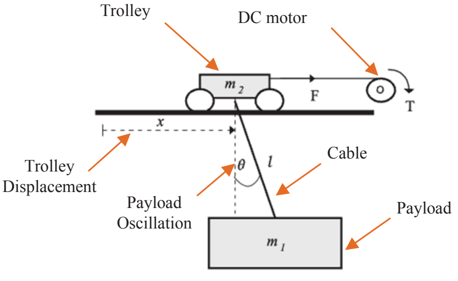


Figure 1. Schematic diagram of GCS.

The system parameters are shown in Table 1.

Table 1. System parameters.

No	System Parameters			
	Parameter	Symbol	Value	Unit
1	Payload mass	m_1	1	kg
2	Trolley mass	m_2	5	kg
3	Cable length	l	0.75	m
4	Gravitational	g	9.81	m/s^2
5	Damping coefficient	B	12.32	Ns/m
6	Resistance	R	2.6	Ω
7	Torque constant	K_T	0.007	Nm/A
8	Electric constant	K_E	0.007	Vs/rad
9	Radius of pulley	r_P	0.02	m
10	Gear ratio	z	15	-

Several methods can be used to model the GCS. From the investigations, it is found that the Lagrange's equation is more suitable to derive the mathematical expression for modeling the system. The GCS has two independent generalized coordinates namely trolley displacement, x and payload oscillation, Θ. The standard form for Lagrange's equation is given in Equation 1:

$$\frac{d}{dt}\left[\frac{\partial L}{\partial \dot{q}_i}\right]-\frac{\partial L}{\partial q_i}=Q_i \tag{1}$$

where L, Q_i and qi represent Lagrangian function, nonconservative generalized forces and independent generalized coordinate. The Lagrangian function can be written as in Equation 2:

$$L = T - P \tag{2}$$

with T and P are respectively kinetic and potential energies. Kinetic and potential energies can be derived as in Equation 3:

$$L = \frac{1}{2}\left(m_1 \dot{x}^2 + m_2 \dot{x}^2 + m_1 l^2 \dot{\theta}^2\right) + m_1 \dot{x}\dot{\theta}\, l \cos\theta \tag{3}$$

Solving for Equation (1) yields nonlinear differential equations as in Equation 4 and Equation 5:

$$(m_1 + m_2)\ddot{x} + m_1 l \ddot{\theta}\cos\theta - m_1 l\, \dot{\theta}^2 \sin\theta + B\dot{x} = F \tag{4}$$

$$m_1 l^2 \ddot{\theta} + m_1 l \ddot{x}\cos\theta + m_1 g l \sin\theta = 0 \tag{5}$$

By considering the dynamic of DC motor, differential equations with their effects are derived where V is an input voltage. Thus, a complete nonlinear equation of GCS can be obtained as in Equation 6 and Equation 7:

$$V = \left[\frac{RBr_P}{K_T z} + \frac{K_E z}{r_P}\right] + \left[\frac{Rr_P}{K_T z}\right](m_1 l)\left[\ddot{\theta}\cos\theta - \dot{\theta}^2 \sin\theta\right] + \left[\frac{Rr_P}{K_T z}\right](m_1 + m_2)\ddot{x} \tag{6}$$

$$m_1 l^2 \ddot{\theta} + m_1 l \ddot{x}\cos\theta + m_1 g l \sin\theta = 0 \tag{7}$$

3.0 CONTROL ALGORITHM

To achieve both control objectives which are precise positioning of a trolley and low payload oscillation, a control structure that combines PID and PD controllers as shown in Figure 2 is proposed. The PID controller is utilized for positioning control whereas the PD controller is implemented for reducing the payload oscillation. Thus, there are five controller gains need to be tuned concurrently. The nonlinear dynamic model of the GCS in Equations 6 and 7 is to be simulated with the PID-PD controller gains. As tuning to obtain optimal performance of the system is hard, MOPSO algorithm is developed and used to calculate optimal controller gains. Moreover, this study involves multi-objective problems where several system response specifications have to satisfy.

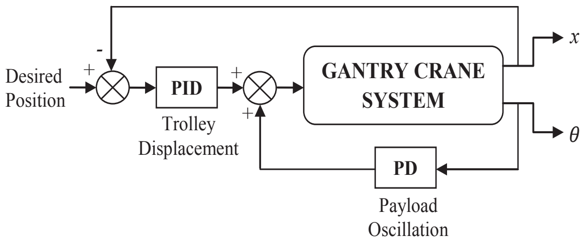


Figure 2. Control structure with five (PID and PD) controller gains.

Simulation exercises are conducted with Intel Core i5-2450M Processor, 2.5GHz, 6GB RAM, Microsoft Window 7 and MATLAB as a simulation platform. The GCS model with nonlinear differential equations in Equation 6 and 7 are designed via Simulink. With an input voltage, two system responses namely trolley displacement, x and payload oscillation, θ are examined.

4.0 MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION

In the original PSO (Kennedy et al., 1995), only a single objective function problem can be solved by using the PSO algorithm. This approach cannot be used to solve the real problem, which consists of multiple objective functions. Therefore, the introductory of Multi Objective Particle Swarm Optimization (MOPSO) has helped a lot in solving the multi-objective problem. Many types of MOPSO have been proposed by researchers (Kitamuraet et al., 2005; Sharafet et al., 2009; Fdhilaet et al., 2011; Brittoet et al., 2012; Jaafar et al., 2013; Jaafaret et al., 2014) and the most popular method is using Linear Weight Summation (LWS) approaches.

Figure 3 show the flow chart for MOPSO in searching the five optimal GCS parameters (PID and PD) by considering the steady-state error (SSE), overshoot (OS) and settling time (Ts) as the objective functions in the system. As shown in the initial stage, a set of initial random values, which represents the initial gantry crane gain controller (three for PID controller and two for PD controller), is generated. These random values are produced based on the range that is set by the user. Next, the individual objective function result is calculated and fitness for each particle is determined based on LWS technique. Since there are three objectives function that are considered in this analysis (steady state error, overshoot and settling time), the formula for the "Fitness" can be written as in Equation 8:

$$Fitness_i = w_{SSE}(SSE)_i + w_{OS}(OS)_i + w_{Ts}(Ts)_i \tag{8}$$

where w_{XX} is the weight value for the objective functions. The result of this Fitness value is used to determine the local best, P_{best} and global best, G_{best} parameters for the updating process. The P_{best} is set as the current position and G_{best} is set as the best initial particle. The remaining processes (updating, check limit and stopping criterion) for solving the optimization problem in the MOPSO algorithm using LWS approaches are similar to the original PSO.

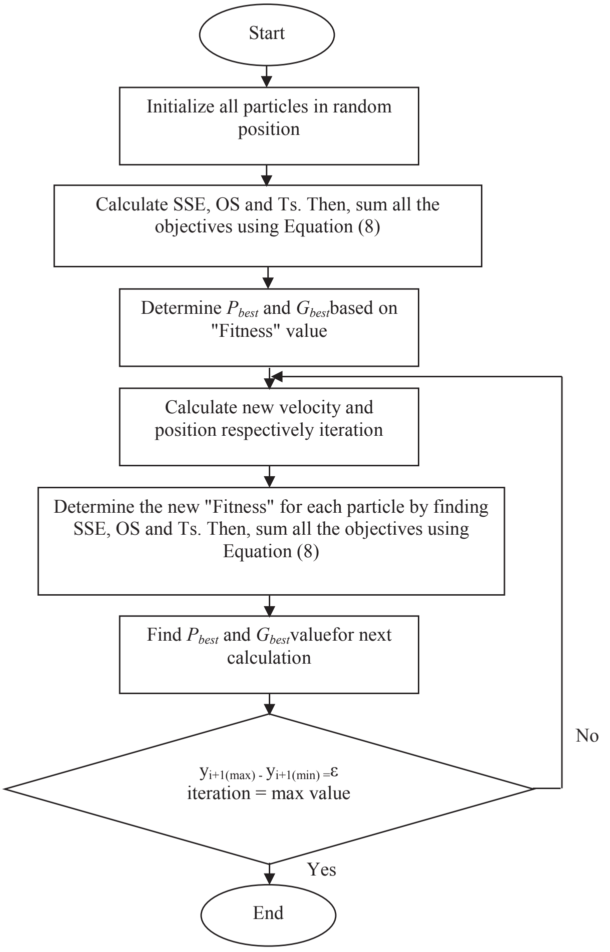


Figure 3. Flow chart of MOPSO in determining GCS parameters.

5.0 RESULTS AND DISCUSSION

In order to observe the effectiveness of multi-objective implementation, four cases with different settings of weight summation are examined as shown in Table 2. The highest weight value is set at 0.7 while the lowest value of weight is 0.1.

Table 2. Different setting of weight summation.

Case	Linear Weight Summation approch		
	w_{SSE}	w_{OS}	w_{Ts}
1	0.1	0.7	0.2
2	0.7	0.2	0.1
3	0.2	0.1	0.7
4	0.1	0.45	0.45

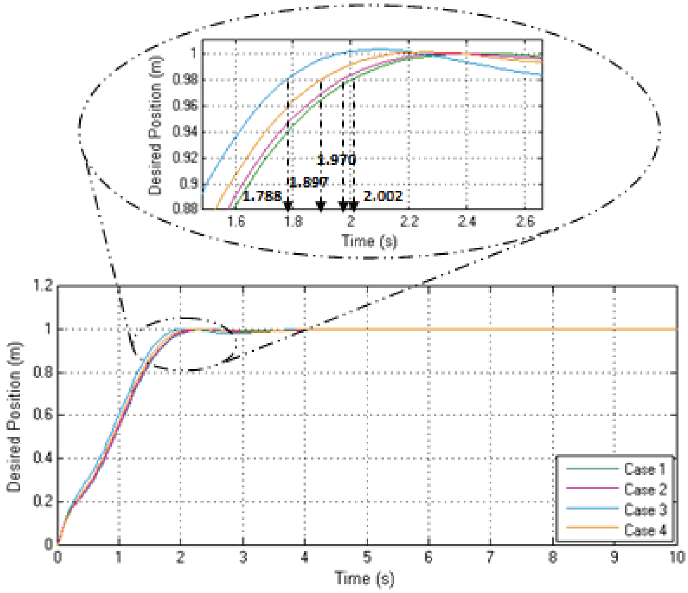
For Case 1, w_{OS} is set as the highest weight value to indicate the highest priority for overshoot. Then, w_{SSE} and w_{Ts} are set as a high priority for Case 2 and Case 3 respectively. Subsequently, another set of weightage (Case 4) is considered with the lowest priority for w_{SSE} and a similar weightage for w_{OS} and w_{Ts}. The summation of weight value for all cases must be equal to one. The purpose of implementing various cases of weight summation is to observe the weight combinations that produce optimal performance for GCS.

By analyzing Cases 1 to 4, it is shown that the proposed LWS approach is able to find optimal performance for GCS according to desired specifications. Setting of weightage values indicates user priority of certain time response specifications. It is also noted that with the control structure, controller gains that produces zero SSE can be obtained with the algorithm although SSE is chosen as lowest priority. According to the results, Case 4 has successfully provided the best optimal performance by which the trolley achieves the desired position with satisfactory response and zero SSE. A satisfactory payload oscillation response is also obtained. Specifications of trolley displacement and payload oscillation performance for all cases are summarized in Table 3.

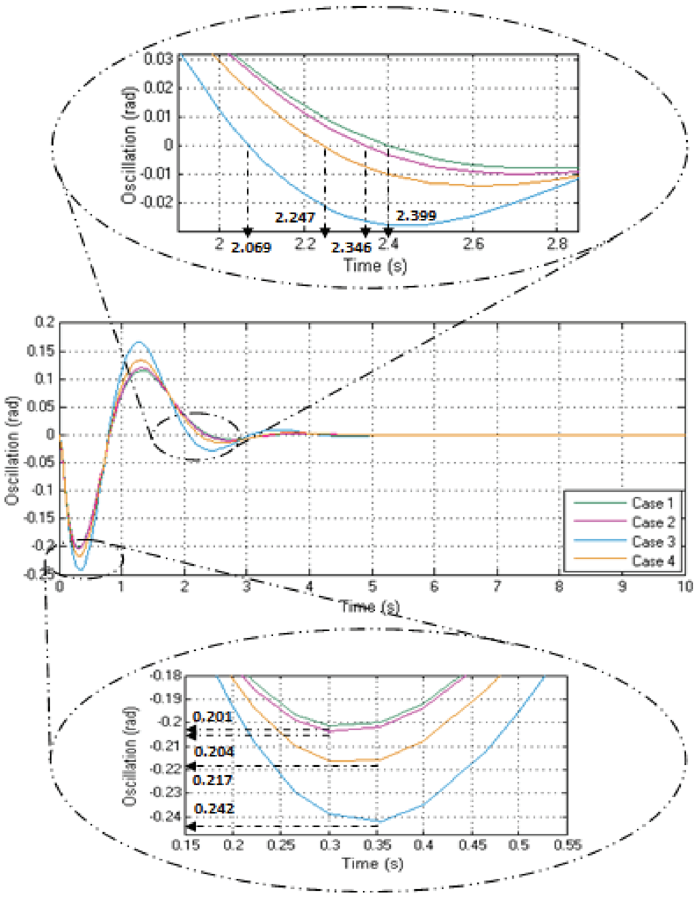
Table 3. Performance of trolley displacement and payload oscillation with different setting LWS approach.

		Weightage			Optimal Performances				
					Trolley Displacement			Payload Oscillation	
		w_{SSE}	w_{OS}	w_{Ts}	*SSE (m)*	*OS (%)*	*Ts (s)*	θ_{max}*(rad)*	*Ts (s)*
Cases	**1**	0.1	0.7	0.2	0.000	0.032	2.002	0.201	2.399
	2	0.7	0.2	0.1	0.000	0.050	1.970	0.204	2.346
	3	0.2	0.1	0.7	0.000	0.237	1.788	0.242	2.069
	4	0.1	0.45	0.45	0.000	0.156	1.897	0.217	2.247

Simulation results are shown in Figure 4(a) and 4(b) for trolley displacement and payload oscillation respectively. Using the PID-PD control structure, the trolley moves to the desired position with zero SSE for all cases. As described earlier, Case 4 provides the best response when OS and Ts are given equal priority. Similarly, Case 4 gives a satisfactory payload oscillation response as compared to the other cases as shown in Figure 4.



(a)



(b)

Figure 4. Performances of GCS based on various cases of LWS
(a) Trolley displacement (b) Payload oscillation.

6.0 CONCLUSION

As a conclusion, selection of weight depends on the needs of a user whether SSE, OS or Ts are set as a priority. The percentage of OS can be minimized by setting higher value of w_{OS} but the time taken to oscillate in one complete cycle is increased. Ts can also be minimized by setting w_{Ts} as higher priority. By minimizing the Ts, the time taken to oscillate in one complete cycle also can be reduced. Variation of w_{SSE} does not affect SSE since it can be eliminated by using lower priority of w_{SSE}. Therefore, the suitable weight combinations are needed to balance the performance of trolley displacement and payload oscillation. According to this analysis, Case 4 is the most suitable weight summation where it gives zero SSE, minimum OS and less Ts.

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