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# Optimal Performance of a Nonlinear Gantry Crane System via Priority-based Fitness Scheme in Binary PSO Algorithm

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**Abstract.** This paper presents development of an optimal PID and PD controllers for controlling the nonlinear gantry crane system. The proposed Binary Particle Swarm Optimization (BPSO) algorithm that uses Priority-based Fitness Scheme is adopted in obtaining five optimal controller gains. The optimal gains are tested on a control structure that combines PID and PD controllers to examine system responses including trolley displacement and payload oscillation. The dynamic model of gantry crane system is derived using Lagrange equation. Simulation is conducted within Matlab environment to verify the performance of system in terms of settling time ( $T_s$ ), steady state error (SSE) and overshoot (OS). This proposed technique demonstrates that implementation of Priority-based Fitness Scheme in BPSO is effective and able to move the trolley as fast as possible to the various desired position.

## 1. Introduction

Limitations of manpower makes gantry crane system are always required for handling heavy load system. It aims to facilitate the delivery of heavy loads with accurate position. However, the crane acceleration is required for motion and induces undesirable load swing [1]. If the speed of trolley is increased, the oscillation of payload become larger and causes the payload difficult to settle down. Thus, position control is difficult and requires a relatively long time for unloading. In order to attain positional accuracy of the gantry crane, a control mechanism that account for positioning of the trolley and oscillation of the payload are required.

Several control techniques have been proposed previously for controlling the gantry crane system. However, PID control schemes based on the classical control theory have been widely used for various industrial control systems for a long time [2]. PID controller is seen as a good prospect due to simple

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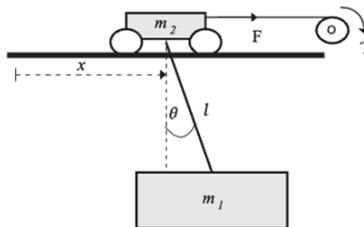
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structure and robust performances in a wide range of operating conditions. Thus, PID controller is chosen and used for this work. However, it has some difficulties in tuning the PID parameters. Therefore, various investigations on intelligent techniques have been conducted to optimize PID parameters. For instance, Genetic Algorithm (GA), Artificial Bee Colony (ABC) algorithm, Ant Colony Algorithm (ACA) and many more was proposed to optimize the parameter of the controller in designing of a nonlinear system. It has flexible and adaptive characteristic in order to find the PID parameters. Nevertheless, since Binary Particle Swarm Optimization (BPSO) is well known compared to the other of some optimization method, thus it is being chosen to be implemented for this work.

## 2. Nonlinear Model of a Gantry Crane System

Figure 1 shows a schematic diagram of a gantry crane system that is considered in this work. The parameters of  $m_1$ ,  $m_2$ ,  $l$ ,  $x$ ,  $\theta$ ,  $T$  and  $F$  are payload mass, trolley mass, cable length, horizontal position of trolley, swing angle, torque and driving force respectively. Nonlinear model of the gantry crane system is modeled based on [3]. 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. The system parameters are shown in Table 1.



**Figure 1.** Schematic diagram of a Gantry Crane System [3]

**Table 1.** System parameters

Parameters	Value (Unit)	Parameters	Value (Unit)
Payload mass ( $m_1$ )	1.0 kg	Resistance ( $R$ )	2.6 $\Omega$
Trolley mass ( $m_2$ )	5.0 kg	Torque constant ( $K_T$ )	0.007 Nm/A
Cable length ( $l$ )	0.5 m	Electric constant ( $K_E$ )	0.007 Vs/rad
Gravitational ( $g$ )	9.81 m/s <sup>2</sup>	Radius of pulley ( $r_P$ )	0.02 m
Damping coefficient ( $B$ )	12.32 Ns/m	Gear ratio ( $z$ )	15.0

## 3. Modeling of a Gantry Crane System

Several methods can be used to model the gantry crane system. 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,  $\theta$ . The standard form for Lagrange's equation is given as:

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

where  $L$ ,  $Q_i$  and  $q_i$  represent Lagrangian function, nonconservative generalized forces and independent generalized coordinate. The Lagrangian function can be written as:

$$L = T - P \quad (2)$$

with  $T$  and  $P$  are respectively kinetic and potential energies. This relationship involved in calculating on how it is related to be more flexible coordinates. Kinetic and potential energies can be derived as:

$$L = \frac{1}{2}(m_1\dot{x}^2 + m_2\dot{x}^2 + m_1l^2\dot{\theta}^2) + m_1\dot{x}\dot{\theta}l \cos \theta + m_1gl \cos \theta \quad (3)$$

Solving for equation (1) yields nonlinear differential equations as:

$$(m_1 + m_2)\ddot{x} + m_1l\ddot{\theta} \cos \theta - m_1l\dot{\theta}^2 \sin \theta + B\dot{x} = F \quad (4)$$

$$m_1l^2\ddot{\theta} + m_1l\ddot{x} \cos \theta + m_1gl \sin \theta = 0 \quad (5)$$

Since the dynamic DC motor is included in this gantry crane model, differential equations with their effects is derived. By considering the dynamic of DC motor, a complete nonlinear differential equation of the gantry crane can be obtained as equation (6) and (7) where  $V$  is an input voltage.

$$V = \left[ \frac{RB r_p}{K_T Z} + \frac{K_E Z}{r_p} \right] + \left[ \frac{R r_p}{K_T Z} \right] (m_1 l) [\ddot{\theta} \cos \theta - \dot{\theta}^2 \sin \theta] + \left[ \frac{R r_p}{K_T Z} \right] \dot{x} \quad (6)$$

$$m_1l^2\ddot{\theta} + m_1l\ddot{x} \cos \theta + m_1gl \sin \theta = 0 \quad (7)$$

Thus, PID and PD controllers are implemented for this nonlinear gantry crane as shown in figure 3.

#### 4. Priority-based Fitness Binary Particle Swarm Optimization (PFBPSO)

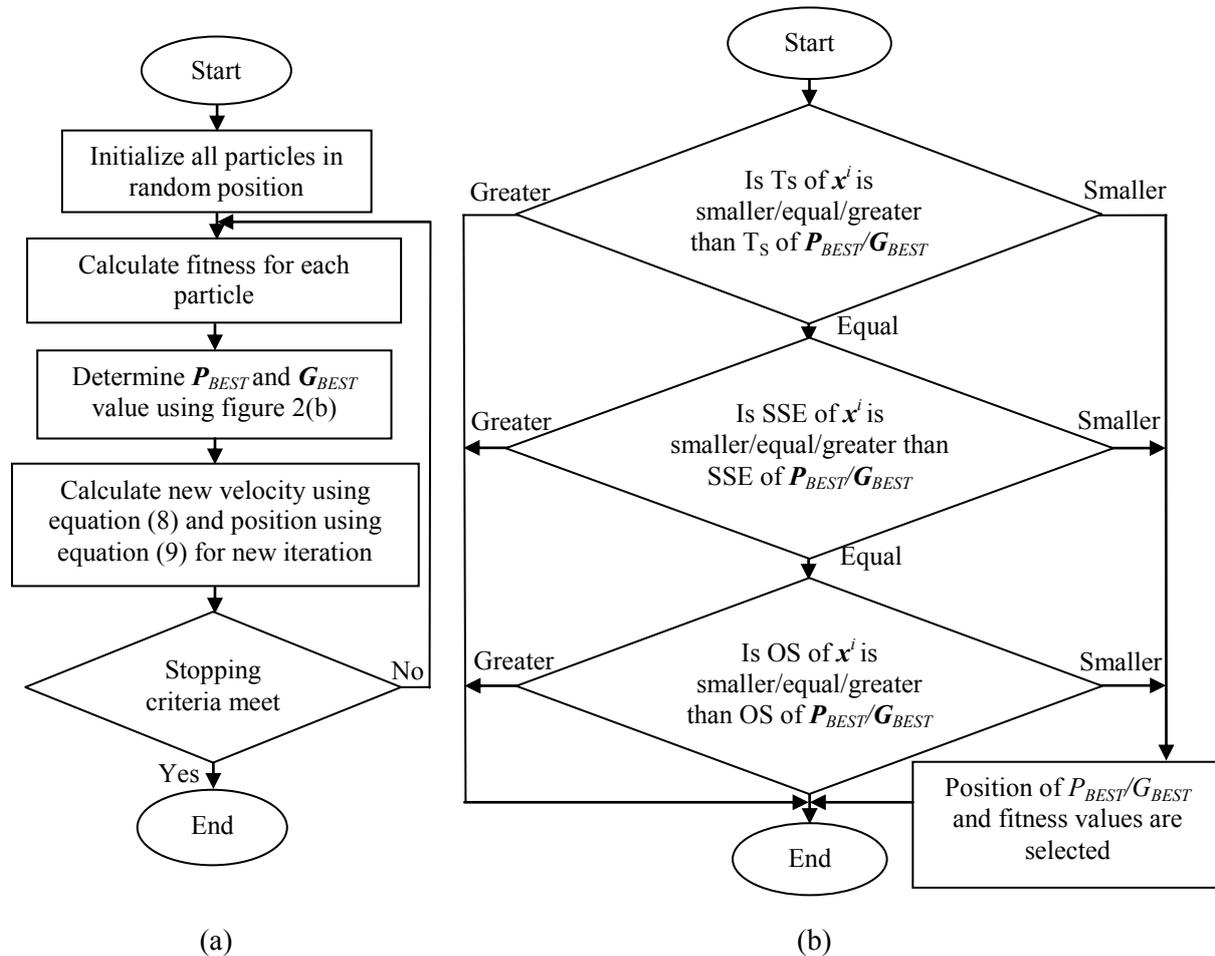
The basic PSO is developed by Kennedy and Eberhart in 1995 [4]. It based on behaviors of fish schooling and bird flocking in order to search and move to the food with certain speed and position. It has been applied successfully and applied easily to solve various function optimization problems especially for nonlinear models. In 1997, Binary PSO (BPSO) has been introduced to solve discrete optimization problem [5]. Applications of BPSO can be seen in many engineering problems, such as routing in VLSI, computational biology, job scheduling and agriculture.

In this research, a new method of Priority-based Fitness Binary Particle Swarm Optimization (PFBPSO) is proposed for tuning of PID and PD parameters. In this work, settling time ( $T_s$ ) is set as highest priority, followed by steady state error (SSE) and overshoot (OS). Figure 2 illustrated the PFBPSO process where the  $P_{BEST}$  and  $G_{BEST}$  are updated according to the priority. The particles find for the local best,  $P_{BEST}$  and subsequently global best,  $G_{BEST}$  for each iteration in order to search for optimal solution. Each particle is assessed by fitness function. Thus, all particles try to replicate their historical success and in the same time try to follow the success of the best agent. It means that the  $P_{BEST}$  and  $G_{BEST}$  are updated if the particle has a minimum fitness value compared to the current  $P_{BEST}$  and  $G_{BEST}$  value. Nevertheless, only particles that within the range of the system's constraint is accepted. The new velocity can be calculated and as in equation (8).

$$v^{i+1} = \omega v^i + c_1 r_1 (P_{BEST} - x^i) + c_2 r_2 (G_{BEST} - x^i) \quad (8)$$

where  $r_1$  and  $r_2$  represent random function values [0,1] while  $c_1$  is cognitive component and  $c_2$  is social component. Next, new particles are updated using equation (9) based on the sigmoid concept which is probability of the normal distribution. The all five parameters are obtained based on binary numbers (either 0 or 1) and then converted into decimal number that represents  $K_p$ ,  $K_I$ ,  $K_D$ ,  $K_{PS}$  and  $K_{DS}$ .

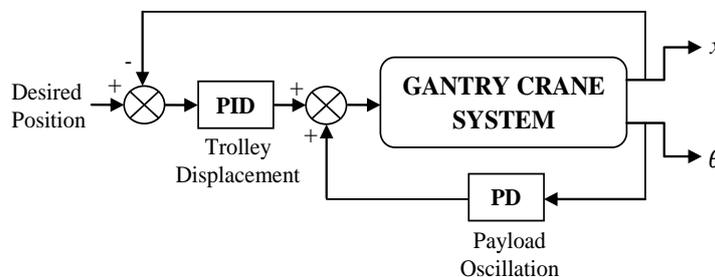
$$sigmoid = \begin{cases} 1, rand < \frac{1}{1 + e^{-v^{i+1}}} \\ 0, rand \geq \frac{1}{1 + e^{-v^{i+1}}} \end{cases} \quad (9)$$



**Figure 2.** The flow chart of PFBPSO in determining gantry crane system parameters  
 (a) Process of PFBPSO algorithm (b) Updated rules for  $P_{BEST}$  and  $G_{BEST}$

**5. Implementation, Results and Discussion**

In this work, a control structure that combines PID and PD controllers as shown in figure 3 is proposed. For this structure, PID controller is used for the positioning control meanwhile the PD controller is used for adjusting the payload oscillation. Therefore, PFBPSO algorithm is designed to tune and find all of these five optimal parameters of controllers.



**Figure 3.** Control structure with five controller gains (PID and PD)

Simulation exercises are conducted with Intel Core i5-2450M Processor, 2.5GHz, 6GB RAM, Microsoft Window 7 and MATLAB as a simulation platform. The gantry crane system model with nonlinear differential equations in equation (6) and (7) are designed via Simulink. With an input

voltage, two system responses namely trolley displacement and payload oscillation are examined. In this study, 20 particles are considered with 100 iterations. As default values,  $c_1$  and  $c_2$  are set as 2. The initial value of  $\omega$  is 0.9 and linearly decreased to 0.4 at some stage in iteration. Table 2 shows the optimal PID and PD parameters are obtained using the PFBPSO algorithm.

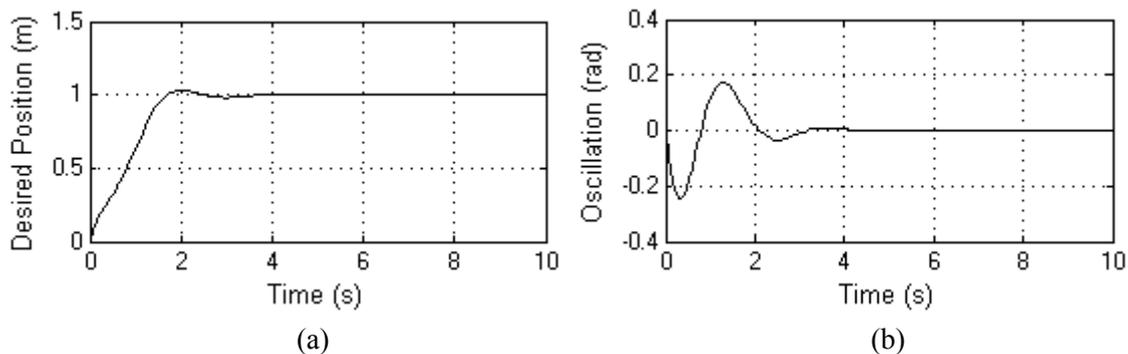
**Table 2.** Optimal PID and PD parameters using PFBPSO

Controller Gains	Binary (12 Bits)	Parameters
$K_P$	011011.001100	27.188
$K_I$	000000.010010	0.005
$K_D$	001011.011100	11.438
$K_{PS}$	100000.110011	32.797
$K_{DS}$	000001.100000	1.500

The control structure in figure 3 is then simulated with the PFBPSO tuned controller parameters. Figure 4(a) and 4(b) shows the trolley displacement and payload oscillation responses respectively with payload of 1.0 kg and desired position at 1.0 m. It is noted with the proposed algorithm, zero SSE with low OS (1.691 %) and  $T_s$  (1.743 s) of displacement response is achieved. Moreover, low payload oscillation is observed. Table 3 summarizes the performances of the gantry crane system that obtained with the controller.

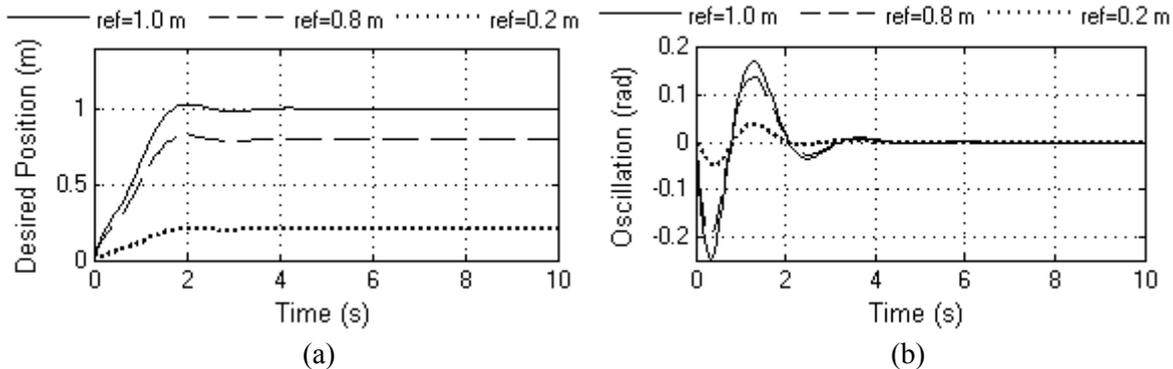
**Table 3.** Control performances with payload 1.0 kg and desired Position 1.0 m

Performances	Trolley Displacement			Payload Oscillation	
	Steady State Error, SSE (m)	Overshoot, OS (%)	Settling Time, $T_s$ (s)	Max. Angle, $\Theta$ (rad)	One Cycle Oscillation, T (s)
Performances	0.000	1.691	1.743	0.249	2.038



**Figure 4.** Performance of (a) trolley displacement (b) payload oscillation with payload 1.0 kg and desired Position 1.0 m

Subsequently, it is desirable to examine the controller's performance under various desired positions. Figure 5 shows the system responses with desired positions at 1.0 m, 0.8 m and 0.2 m. It is shown that the system response successfully track desired positions. In the PFBPSO algorithm, overshoot, settling times and payload oscillation are affected with various desired positions. Therefore, SSE is achieved for all conditions. Table 4 summarizes simulation results with various desired positions.



**Figure 5.** System response with various desired positions at 1.0 m, 0.8 m and 0.2 m  
(a) trolley displacement (b) payload oscillation

**Table 4.** Control performances with payload 1.0 kg and various desired position

Various Desired Position	Trolley Displacement			Payload Oscillation	
	Steady State Error, SSE (m)	Overshoot, OS (%)	Settling Time, $T_s$ (s)	Max. Angle, $\Theta$ (rad)	One Cycle Oscillation, T (s)
1.0 m	0.000	1.691	1.743	0.249	2.038
0.8 m	0.000	1.702	1.721	0.214	2.029
0.2 m	0.000	1.711	1.699	0.193	2.021

## Conclusion

This paper has presented design of an optimal PID controller for control of a gantry crane system. Nonlinear differential equations of the system has been derived and used for verification of control algorithm. In this work, the PFBPSO algorithm has been proposed in order to find all of these five optimal controller gains. The optimal gains have been tested based on a control structure that combines PID and PD controllers. System responses including trolley displacement and payload oscillation have been examined. Simulation results have shown that the controller is effective to move the trolley as fast as possible to the various desired position with low payload oscillation based on priority-based fitness scheme.

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