PSO-Tuned PID Controller for a Nonlinear Gantry Crane System

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***Abstract*—This paper presents development of an optimal PID controller for control of a nonlinear gantry crane system. An improved PSO algorithm based on a priority-based fitness approach is implemented for finding optimal PID parameters. The system dynamic model is derived using Lagrange equation. A combination of PID and PD controllers are utilized for position and oscillation control of the system. System responses including trolley displacement and payload oscillation are observed and analyzed. Simulation is conducted within Matlab environment to verify the performance of the controller. It is demonstrated that the controller is effective to move the trolley as fast as possible to the desired position with low payload oscillation technique.**

***Index Terms*—Computational Intelligence, Gantry crane, Particle Swarm Optimization, PID, Swarm Intelligence.**

I. Introduction

Gantry cranes are commonly used in material handling system in factories, warehouse, shipping yards and nuclear facilities where heavy loads must be moved with extraordinary precision. However, the crane acceleration, required for motion, always induces undesirable load swing [1]. This unavoidable frequently load swing causes efficiency drop, load damages and even accidents. It is desirable to move the trolley to a required position as fast as possible with low payload oscillation. At higher speed, these sway angles become larger and significant, and cause the payload hard to settle down when unloading. To attain positional accuracy of the gantry crane, a control mechanism that account for position of the trolley and oscillation of the payload is required.

Various attempts for control of gantry craned have been proposed. However, despite the advent of many control theories and techniques, PID control is still one of the most widely used control algorithms in industries. The controller has also been implemented on the system. Chang et al [2] combined PID and Fuzzy control to achieve a robust controller for an overhead crane. PID+Q controller has also been developed to reduce payload swing angle [3]. However, this work focused only on the reduction of payload sway.

In PID control, tuning of PID parameters is very crucial. It is desirable to find optimal parameters that give satisfactory system response. Recently, besides the Zigler-Nichols tuning method, several investigations have been conducted for optimization of PID parameters especially based on intelligent techniques. For instance, Genetic Algorithm has been applied to tune PID for automatic gantry crane [4]. In addition, Ant Colony Optimization was proposed to optimize the parameter of the controller in designing of a nonlinear PID controller. Satisfactory overall performance of the system has been demonstrated with the controller [5]. Another optimization technique that can be utilized for control of gantry carne is Particle Swarm Optimization, PSO algorithm which was introduced in 1995 [6].

The main strength of PSO is its fast convergence compares with many global optimizations. For that reason, PSO is highly demanded by researchers in tuning PID controller parameters. One of the successful applications was tuned PID controller parameters applied to a dynamic first order system [7]. PSO-tuned PID controller was also tested on a magnetic levitation system and good results have been shown [8]. Furthermore, Solihin et al [9] has also investigated the application of PSO for obtaining PID parameters for a gantry crane system.

This paper presents development of an optimal PID controller for control of a nonlinear gantry crane system. In this work, optimal PID parameters are obtained with an improved PSO algorithm based on a priority approach. Initially the system nonlinear dynamic model is derived using Lagrange equation. Subsequently a control structure with two PID controllers is proposed for position control of the trolley and reduction of payload oscillation. The proposed PSO algorithm is used to find optimal parameters according to priority in time response specifications namely steady-state error, overshoot and settling time. Simulation results have demonstrated satisfactory responses with the proposed controller under various loading conditions.

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II. NON LINEAR MODEL OF A GANTRY CRANE SYSTEM

Fig. 1 show a schematic diagram of a gantry crane considered in this work. 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. Nonlinear model of the gantry crane system is modeled based on [9]. Similar system parameters as in Table I is also used in this investigation.

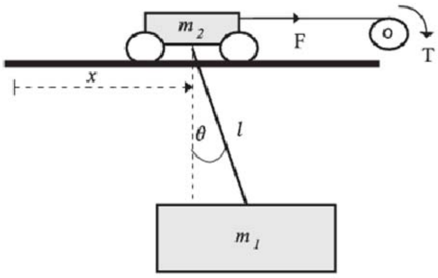

Fig. 1. Schematic diagram of a gantry crane system [9]

TABLE I. SYSTEM PARAMETERS

Parameters	Value
Payload mass (m_1)	1 kg
Trolley mass (m_2)	5 kg
Cable length (l)	0.75 m
Gravitional (g)	9.81 m/s^2
Damping Coefficient (B)	12.32 Ns/m
Resistance (R)	2.6 Ω
Torque constant (K_T)	0.007 Nm/A
Electric constant (K_E)	0.007 Vs/rad
Radius of pulley (r_P)	0.02 m
Gear ratio (z)	15

III. MODELING OF A GANTRY CRANE SYSTEM

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

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

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

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

with T and P are respectively kinetic and potential energies. Thus, the Lagragian function can be obtained as:

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

Solving for Eq. 1 yields nonlinear differential equations as:

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

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

where V is an input voltage. 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 system can be obtained as:

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

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

Thus, PID controller is implemented for this nonlinear gantry crane system as shown in Fig. 3.

IV. PARTICLE SWARM OPTIMIZATION

PSO is one of the artificial intelligence families that was introduced in 1995 by Kennedy and Eberhart [6]. The basic PSO is developed 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 to a wide variety of optimization problems. Due to this, it could be implemented and applied easily to solve various function optimization problems especially for nonlinear models.

For this problem, the particle position in PSO can be modeled as Eq. 8.

$$\mathbf{x}^i = [K_P, K_I, K_D, K_{PS}, K_{DS}] \qquad (8)$$

where $\mathbf{x}$ is the particle position, K_P, K_I, K_D are the proportional, integral, and derivative values of PID controller to control position of the gantry crane, respectively. While K_{PS} and K_{DS} are the proportional, and derivative values of PD controller to control oscillation of the gantry crane.

It is initialized and started with a number of random particles. Initialization of particles is performed using Eq. 9.

$$x^i = x_{min} + rand(x_{max} - x_{min}) \tag{9}$$

where x_{max} and x_{min} are the maximum and minimum values in the search space boundary. Then, the particles find for the local best, P_{BEST} and subsequently global best, G_{BEST} in every 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 and new position can be calculated and as in Eq. 10 and 11.

$$\boldsymbol{v}^{i+1} = \omega \boldsymbol{v}^i + c_1 \boldsymbol{r}_1(\boldsymbol{P}_{BEST} - \boldsymbol{x}^i) + c_2 \boldsymbol{r}_2(\boldsymbol{G}_{BEST} - \boldsymbol{x}^i) \tag{10}$$

$$\boldsymbol{x}^{i+1} = \boldsymbol{x}^i + \boldsymbol{v}^{i+1} \tag{11}$$

where r_1 *and* r_2 represent random function values [0,1] while c_1 is cognitive component and c_2 is social component. The function of ω parameter is to balance between local and global search capabilities [8].

In this research, an improved PSO algorithm using a priority-based fitness approach is proposed for tuning of PID parameters. In this work, steady state error, SSE is set as highest priority, followed by overshoot, OS and settling time, Ts. Fig. 2 illustrated the priority-based fitness approach where the $\boldsymbol{P}_{BEST}$ and $\boldsymbol{G}_{BEST}$ is updated according to the priority: SSE, OS, and Ts.

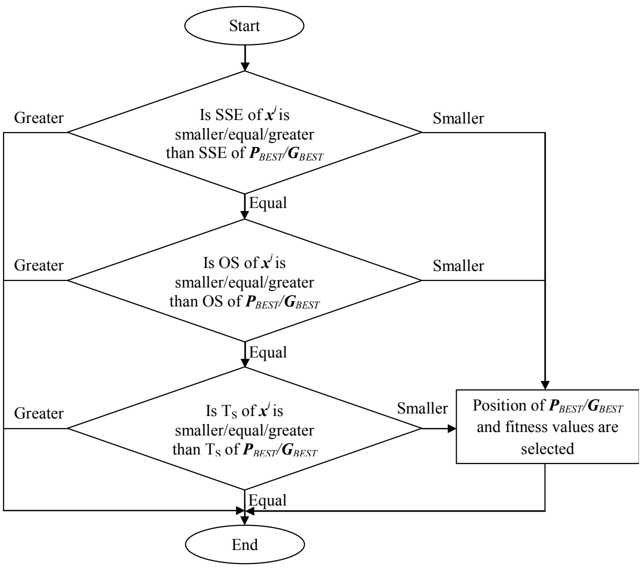

Fig. 2. Updated rules for $\boldsymbol{P}_{BEST}$ and $\boldsymbol{G}_{BEST}$ using priority-based fitness approach

V. Implementation, Results And Discussion

In this work, a control structure that combines PID and PD controllers as shown in Fig. 3 is proposed. For this structure, PID is used for position control and PD is for control of payload oscillation. Therefore five controller gains need to be tuned.

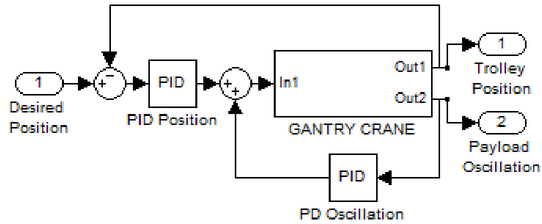

Fig. 3. Control structure with five controller gains (PID and PD)

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 Eq. 6 and 7 is designed via Simulink as shown in Fig. 4. With an input voltage, two system responses namely trolley displacement and payload oscillation are examined.

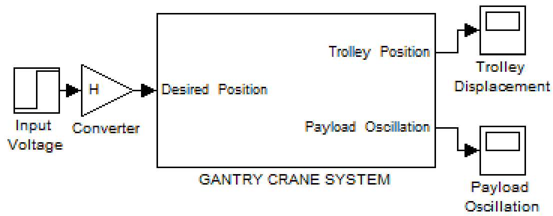

Fig. 4. Nonlinear gantry crane system

The proposed PSO algorithm is used to tune and find five optimal parameters of PID and PD controllers. Fig. 5 show a flowchart of the proposed PSO algorithm for tuning of PID parameters. In this study, 20 particles are considered with 100 iterations. The initial particles are bounded between 0 to 200. As default values, c_1 and c_2 are set as 2. The initial value of ω is 0.9 and linearly decreased to 0.4 at some stage in iteration. Table II shows optimal PID and PD parameters obtained using the improved PSO algorithm.

TABLE II. PID And PD Parameters Based On Optimization

PID Gains	Parameters
K_P	125.1931
K_I	0.0012
K_D	84.7052
K_{PS}	197.9454
K_{DS}	0.0032

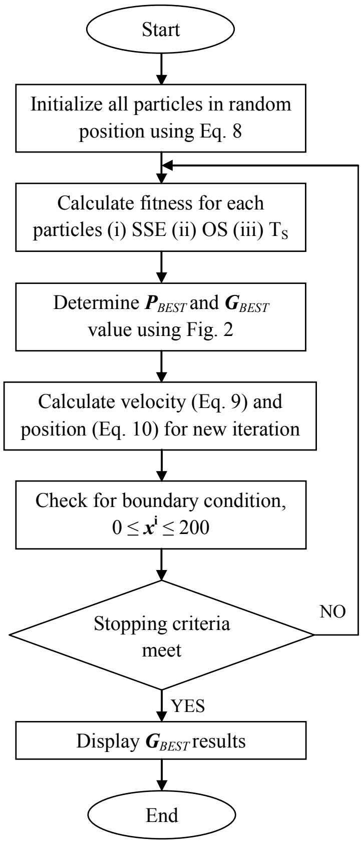

Fig. 5. Implementation of PSO to tune PID parameters

The control structure in Fig. 3 is then simulated with the PSO-tuned controller parameters. Fig. 6 and 7 shows the trolley displacement and payload oscillation responses respectively with payload of 1 kg. It is noted with the proposed algorithm, zero steady state error, SSE with low overshoot, OS and settling time, T_S of displacement response is achieved. Moreover, low payload oscillation is observed. Table III summarizes system specifications obtained with the controller.

TABLE III. CONTROL PERFORMANCES WITH PAYLOAD 1 KG

Performances				
Trolley Displacement			***Payload Oscillation***	
SSE (m)	*OS (%)*	*Ts(s)*	*□max (rad)*	*T(s)*
0.000	2.913	2.247	0.246	2.125

Subsequently, it is desirable to examine the controller's performance under various loading conditions and desired positions. Fig. 8 shows the system responses with payloads of 1 kg, 5 kg and 10 kg. It is noted for all loading conditions,

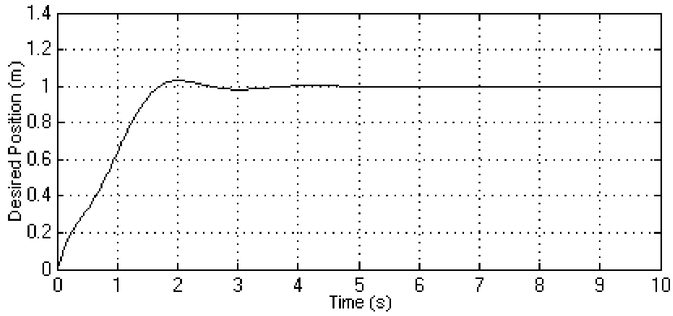

Fig. 6. Trolley Displacement

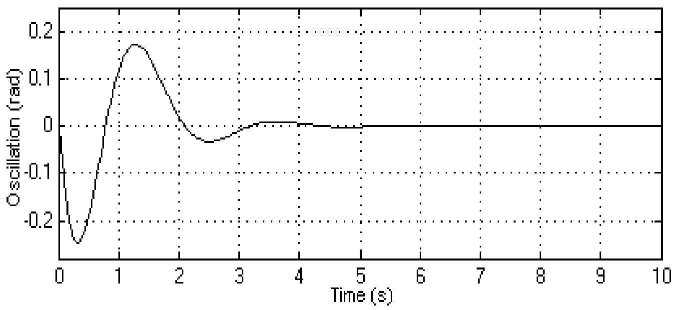

Fig. 7. Payload Oscillation

quite a similar trolley position response is obtained. In all cases zero SSE and less OS and T_S are obtained. However, slightly difference payload oscillation responses are observed with various payloads. Simulation results with a higher payload show less payload oscillation but required more time to settle down. Table IV summarizes simulation results with various payloads.

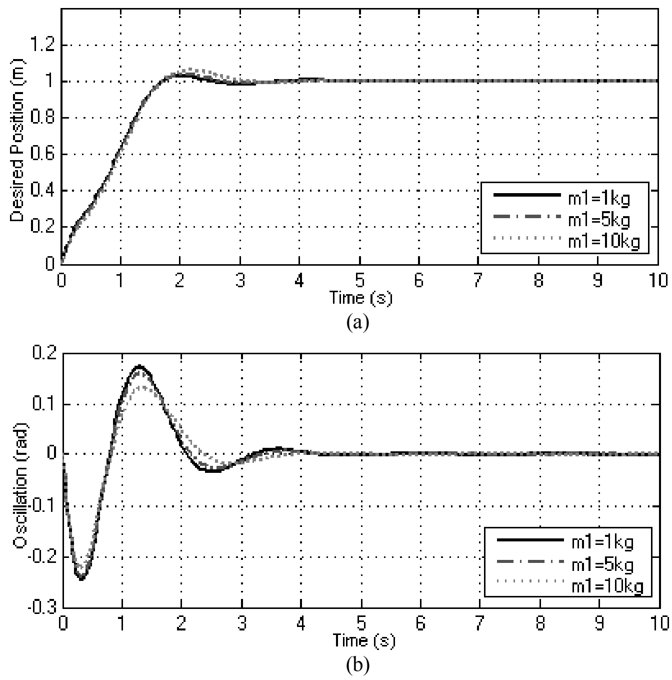

Fig. 8. System Response with Payload of 1 kg, 5 kg and 10 kg
(a) Trolley position (b) Payload oscillation

TABLE IV. PERFORMANCES OF TROLLEY DISPLACEMENT AND PAYLOAD OSCILLATION WITH DIFFERENT PAYLOAD MASS

Payload variable	Performances				
	Trolley Displacement			***Payload Oscillation***	
	SSE (m)	*OS (%)*	*Ts(s)*	*θ max (rad)*	*T(s)*
1 kg	*0.000*	2.913	2.247	0.246	2.125
5 kg	*0.000*	3.568	2.402	0.239	2.232
15 kg	*0.000*	5.393	2.764	0.223	2.497

Fig. 9 shows the system responses with desired positions at 1 m, 0.8 m and 0.2 m. It is shown that the system response successfully track desired positions. As SSE is set at highest priority in the PSO algorithm, zero SSE is achieved for all conditions. However, settling times and payload oscillation is affected with various desired positions. Table V summarizes simulation results with various desired positions.

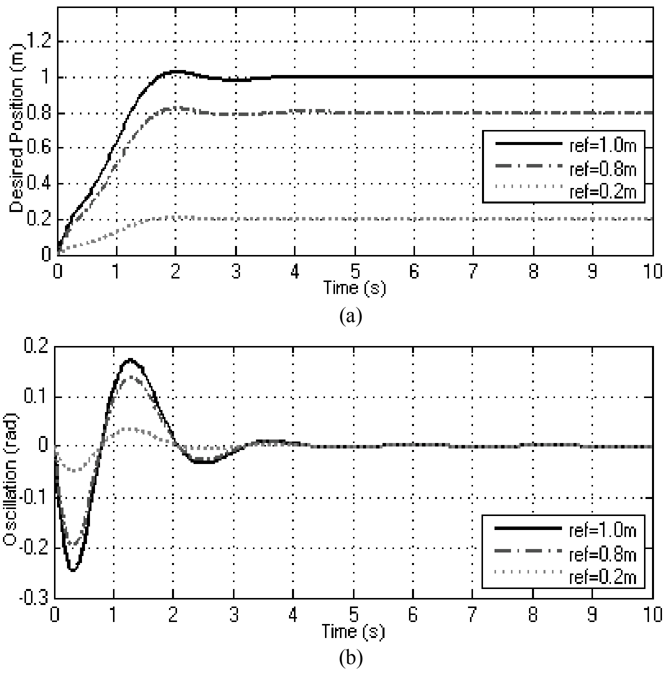

Fig. 9. System Responses with Various Desired Positions
(a) Trolley position (b) Payload oscillation

TABLE V. PERFORMANCES OF TROLLEY DISPLACEMENT AND PAYLOAD OSCILLATION WITH DIFFERENT DESIRED POSITIONS

Desired position variable	Performances				
	Trolley Displacement			***Payload Oscillation***	
	SSE (m)	*OS (%)*	*Ts(s)*	*θ max (rad)*	*T(s)*
1.0 m	*0.000*	2.913	2.247	0.246	2.125
0.8 m	*0.000*	2.920	2.219	0.196	2.111
0.2 m	*0.000*	2.924	2.201	0.049	2.100

VI. 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, an improved PSO algorithm based on a priority-based fitness approach to find optimal controller gains has been proposed. 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 desired position with low payload oscillation.

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