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PSO-BASED PID-PD CONTROLLER OF A GANTRY CRANE WITH PARAMETER UNCERTAINTIES

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Abstract: Cranes suffer from excessive swing due to the parameter uncertainties such as payload hoisting and payload mass which may affect the efficiency of the control performances. This paper presents modelling and optimal control of a gantry crane system subjected to parameter uncertainties. The Lagrange method is used for modelling the gantry crane which is derived from the Lagrange equation. An optimal controller is proposed in the system to obtain an efficient swing reduction and accurate trolley position. The proposed controller consists of two feedback control systems namely PID and PD controller which are utilized for tracking the accurate trolley position and reducing the payload swing angle, respectively. An intelligent optimization method is implemented in this study where the Particle Swarm Optimization (PSO) algorithm is used to find the optimal parameter gains for the controllers. For the robustness test, two cases are considered involving changes in payload mass and cable length. The superiority of the proposed method is confirmed by reduction of 17.7% in the maximum swing response over the comparative method.

Keywords: Sustainability, gantry crane, payload swing suppression, PSO, PID-PD.

Introduction

This project focuses on the control of the Gantry Crane System (GCS) transporting heavy loads from one place to another place with an accurate trolley positioning with payload swing reduction. Due to its flexible framework, the gantry cranes have been used over the past few years in the field of heavy machinery (Pandey *et al*., 2014) and due to its cost-effectiveness and ease of operation, GCS is widely used in the industries, shipping yards, mining sites, power plants, and warehouses (Alhassan *et al*., 2016; Ramli *et al*., 2017). In other works, control of other types of cranes include a rotary crane (Sun *et al*., 2020) cooperative dual rotary crane systems (DRCSs, offshore crane (Chen & Sun, 2021), and tower crane (Roman *et al*., 2019; Fasih *et al*., 2022).

In practical applications, most of the cranes are operated by a human operator which lead to unsatisfactory control tasks (Ramli *et al*., 2020). Hence, a control system for swing reduction is desirable. There are numerous methods for controlling the GCS which include PID-Ziegler-Nichols and hybrid input shaping method for controlling trolley position and reducing payload swing respectively (Mohd Tumari *et al*., 2013)while the proportional integral derivative (PID. Due to non-linearities of gantry crane system, the control parameters obtained from the Ziegler-Nichols method was not sufficient to optimize the PID controller. In addition, the input shaper used to reduce the swing angle was inefficient in terms of incorporating a greater number of impulses which resulted in a slow trolley motion. Other famous method used to control the GCS was an intelligent method such as a Fuzzy-LQR based anti-swing control (Mu *et al*., 2014). However, in terms of efficiency, the Fuzzy-LQR required a longer time of the trolley to settle and reach a stable state.

This study is motivated by the issues of how to precisely obtain the trolley positioning and reduces the swing angle of the payload at the same time with the minimum time required for transporting the payload of crane systems. The gantry crane is used for both lifting and transporting heavy things from a place to another. If the sway angle of the payload cannot be minimized and exceeds the critical limits, then the operation of transporting a load must be stopped at all costs. Several factors prove the importance of the controller to industries such as human operators conventionally will automate the crane manually which is prone to an excessive payload swing caused by a human operator. This excessive payload swing if it is not be controlled properly, it will cause damage to people and surrounding. Besides, the crane contributes to one-third of all construction and maintenance facilities and injuries. A great number of cranes were being utilized but at the same time there were many injuries occurred because of these cranes. There were numerous examples of unfortunate accidents that happened in the past because of this factor due to failure in handling a crane to transport a load to the desired position and location. One of the accidents has occurred in Mecca's Grand Mosque, Saudi Arabia where the tower crane collapsed and recorded at least 107 people have been killed after a crane toppled over, less than 2 weeks before Islam's annual Hajj pilgrimage (Ramli *et al.*, 2017). Moreover, the changes of the system parameters such as cable length and payload mass will induce more payload swinging that eventually cause an unwanted accident happened. The majority of crane control techniques were designed using linearized crane dynamics and usually require for exact model information. However, practical cranes frequently have uncertainties like unknown cable length and payload mass, which significantly degrade the control performance *(Sun et al.*, 2016). Hence, an optimal control based on a nonlinear model is needed to obtain an accurate design of controller.

In this study, the optimal controllers are implemented and Particle Swarm Optimization (PSO) method is utilized to optimize the controllers parameters using a modelled control structure combining both the PID and PD controllers. PSO is one of the artificial intelligence techniques and highly implemented by researchers in optimizing the various controller methods (Mohd Tumari *et al.*, 2013; Shao *et al.*, 2019). Intelligent algorithms offer an ease of execution and efficient optimization due to their ability to treat an inaccurate model (Lazim *et al.*, 2017). Based on the previous research such as in (Jaafar *et al.*, 2012), it has been proved that PSO is one of the efficient optimization techniques and very effective to optimize the controllers parameters. Its main strength lies in a fast convergence as compared to the other optimization techniques (Syed Hussien *et al.*, 2015). The contributions of the paper are:

1) Since most of the industrial cranes are inherently nonlinear, the proposed controller is optimized based on a nonlinear model to obtain an accurate control design.
2) The proposed controller parameters are acquired based on an artificial intelligence method which can effectively suppress payload swing and achieve the accurate trolley position.

Model Description

Based on the 2-D gantry crane schematic diagram as illustrated in Figure 1, a gantry crane system can be modelled using Lagrange approach where x is the horizontal position of the trolley, l is the cable length, θ is the sway angle, m_1 is the mass of the payload, m_2 is the mass of the trolley and F is the force. In the simulation, some assumptions have been made such as tensile force, DC motor are ignored and the cable of the trolley is maseless. The system parameters used in this project are shown in Table 1.

The mathematical equation for modeling the system is derived from the Lagrange equation (Jaafar *et al.*, 2012). There are two separate generalized coordinates of the gantry crane system such as the displacement of the trolley given as x and payload swing angle as θ. The Lagrange equation in the standard form is obtained as:

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

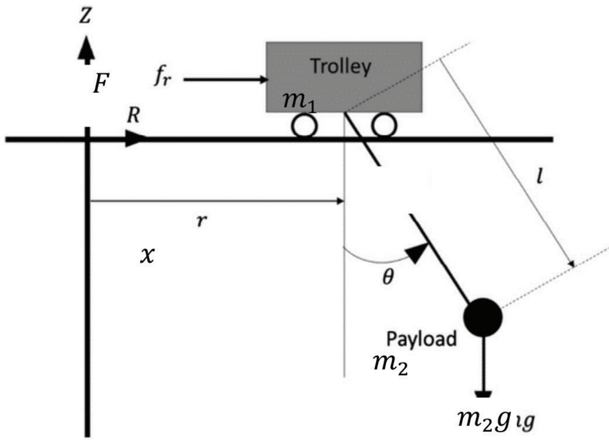


Figure 1: Two-dimensional gantry crane system

Table 1: System parameters

Parameters	
Payload mass (m_1)	1 kg
Trolley mass (m_2)	5 kg
Cable length (l)	0.5 m
Gravitational (g)	9.81 ms^{-2}
Damping coefficient (B)	12.32 Nsm^{-1}

L, q_i and F are known as a Lagrange function equation, nonconservative generalized forces, and independent generalized coordinate. The Lagrange function is given as:

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

For and , both are known as kinetic and potential energy. The Lagrange function is obtained as:

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

Then, obtained non-linear differential equation by solving Eq 1:

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

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

The PID and PD controllers are then implemented for this non-linear gantry crane system. The implementation of PID-PD controller and PSO method are discussed in the next sections.

Controller Design

In this work, a control structure with a combination of PID and PD controller is proposed as shown in Figure 2. The gantry crane is designed using a non-linear differential equation of the Lagrange approach. PID and PD controllers are utilized in the system to track the accurate trolley position and reduce payload swing angle of the crane, respectively. The gain parameters for these controllers such as K_P, K_I, K_D, K_{PS}, and K_{DS} need to be tuned effectively so that the best system performance could be achieved. The control structure of the system is modelled as illustrates in Figure 2. Both of the PID and PD are implemented to control the trolley position and payload swing respectively to achieve the desired performances. The PSO algorithm is used to optimized the controller parameters where the optimal parameters are designed such that the error for the trolley position and payload swing are minimized.

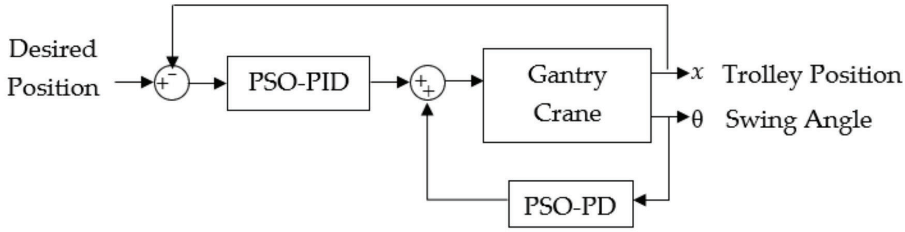


Figure 2: Control structure of the system

Particle Swarm Optimization Technique

The basic PSO is developed based on behaviors of fish schooling and bird flocking to search and move to the food with a certain speed and position (Mohd Tumari *et al*., 2013)while the proportional integral derivative (PID. This optimization has been proved that can be implemented in solving the optimization issues. PSO is about a particle that offers a theoretical solution to an issue. Each particle is assessed by fitness function (Jaafar *et al*., 2012; Ramli *et al*., 2015). Thus, all particles will copy and follow their own or their companion's best rate of success. It uses the best particle performance to get close to the optimum result. PSO will tune all 5 gains used in the controller where the gains are divided into two parts. K_P, K_I, and K_D will control the position of the trolley while K_{PS} and K_{DS} will control the swing angle of oscillation of the payload. To tune all five gains, the iteration is initialized with a random number and this initialization of particles is carried out using the PSO iteration particles formula. Then, the best previous location is recorded which is known as Pbest. And then from Pbest, there is the best particle of all particles which is known as Gbest also is recorded. The velocity of all particles also important and it is included in PSO optimization. The position of This particle of PSO can be modelled as:

$$x^i = [K_P, K_I, K_D, K_{PS}, K_{DS}] \quad (6)$$

x^i is known as the position of all particles. K_P, K_I, K_D are proportional, integral, and derivative gains values of PID controller, respectively, and for K_{PS} and K_{DS} are gain values for PD controller, proportional and derivate values respectively. The initialization of particles started with a casual number of particles. It can be performed using an equation below:

$$x^i = x_{min} + rand(x_{max} - x_{min}) \quad (7)$$

x_{max} and x_{min} above are the values of a boundary search space for maximum and minimum points. The steps to find the solution for the optimization problem are the particles are obligated to find local best, P_{BEST}, and then followed by global best, G_{BEST} for each of iterations process. The particles in the PSO algorithm are accessed by the fitness function. The fitness function will compare the previous value of P_{BEST} and G_{BEST} with the current value. If it has a minimum fitness value, then the P_{BEST} and G_{BEST} will be renewed. Nevertheless, the particles are chosen when they are in the range of the context system constraints only. The working concept of the fitness function is shown in Figure 3.

The new value of P_{BEST} and G_{BEST} are updated by considering an Integral Absolute Error (IAE). Next, the value for velocity and position of the particles can be calculated using the equation below:

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

$$x^{i+1} = x^i + v^{i+1} \quad (8)$$

The unknown and are the function with a casual value of [0,1], while the and are the components of cognitive and the component of social, respectively. The role of the ω parameter is to make sure the stability in searching for local and global value.

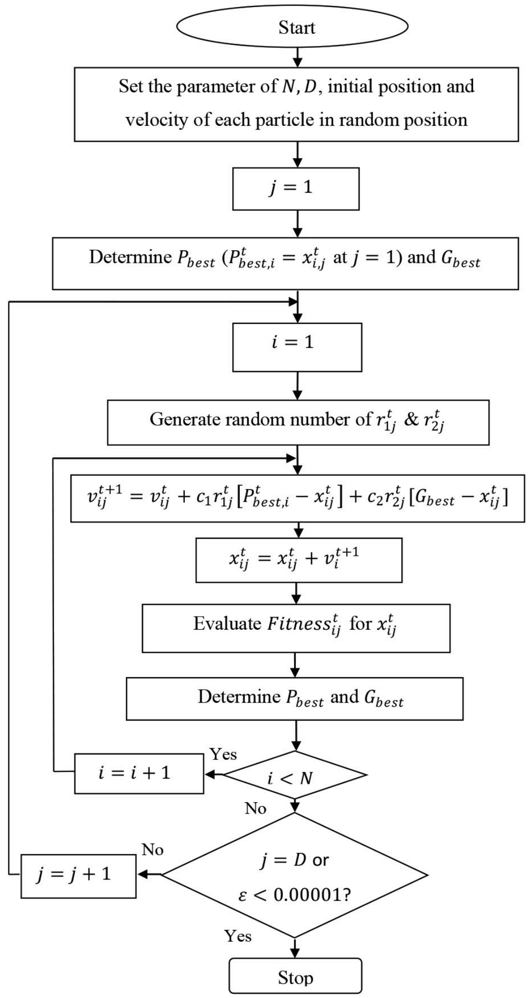


Figure 3. Flowchart of the working concept of fitness function

Results and Discussions

This section presents the simulation works on the gantry crane system using the proposed PID-PD optimized using PSO method and PID-PD optimized using automatic PID tuner application in Simulink was utilized as a comparative method.

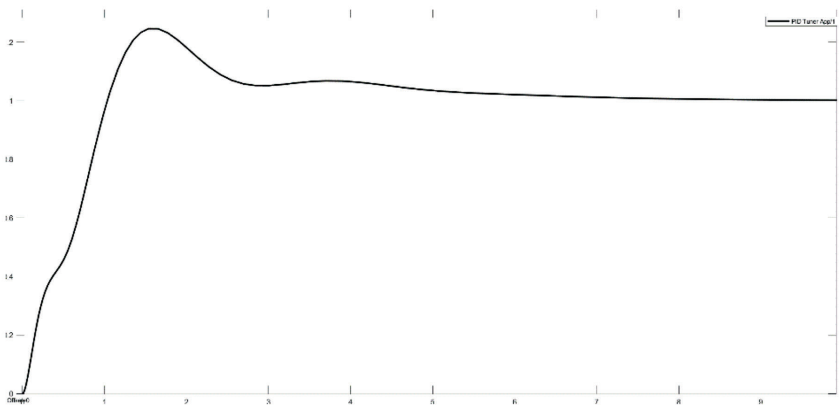
Simulations were carried out using Matlab/Simulink with AMD A9-9420 RADEON R5, 5 COMPUTE CORES 2C+3G, 3.00 GHz, 4.00 GB RAM and Microsoft Window 10. The payload mass of 1.0 kg, cable length of 0.5 m and a desired trolley position of 1.0 m were used. Two system responses were analyzed that are based on trolley position and payload swing angle. For swing response, the controllers were evaluated based on the maximum swing angle (θ_{max}) and the Settling Time (T_S). Hence, a lower θ_{max} and T_S values are desirable where they indicate a higher swing reduction. For trolley response, IAE, OS, and T_S were used to evaluate the controller performance. An IAE indicates the overall performance for trolley response where a lower value of the IAE is desirable. Similarly, lower OS and T_S values are essential for a fast trolley performance.

The step response was used as an input to the system. The controller parameters that were optimized by the automatic PID tuner and PSO can be seen in Table 2.

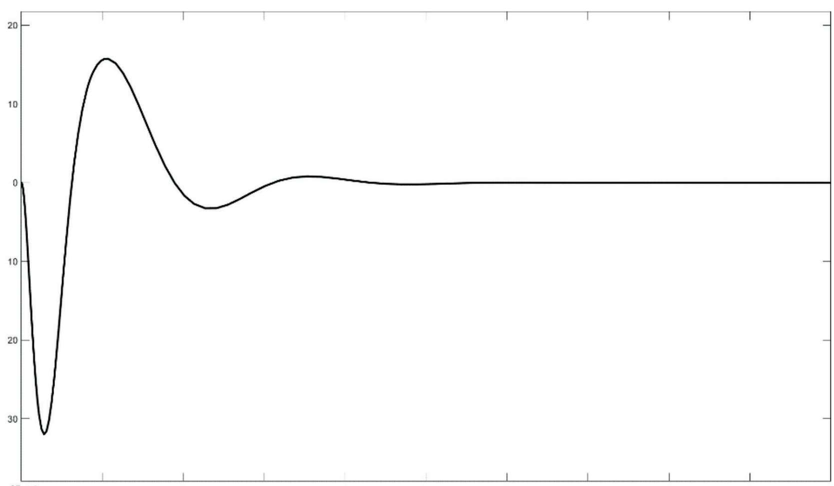
K_P, K_I, K_D, K_{PS}, and K_{DS} were set as tuning parameters in the PSO algorithm to obtain the optimal parameters for the controllers. In the PSO process, several initializations were considered

Table 2: Parameters values of PID-PD using automatic PID tuner and PSO method

Controller Parameters	**Automatic PID Tuner**	**PSO**
K_P	38.9254	25
K_I	12.7771	0
K_D	21.1922	8.8642
K_{PS}	39.3837	14.1392
K_{DS}	14.2640	3.1367



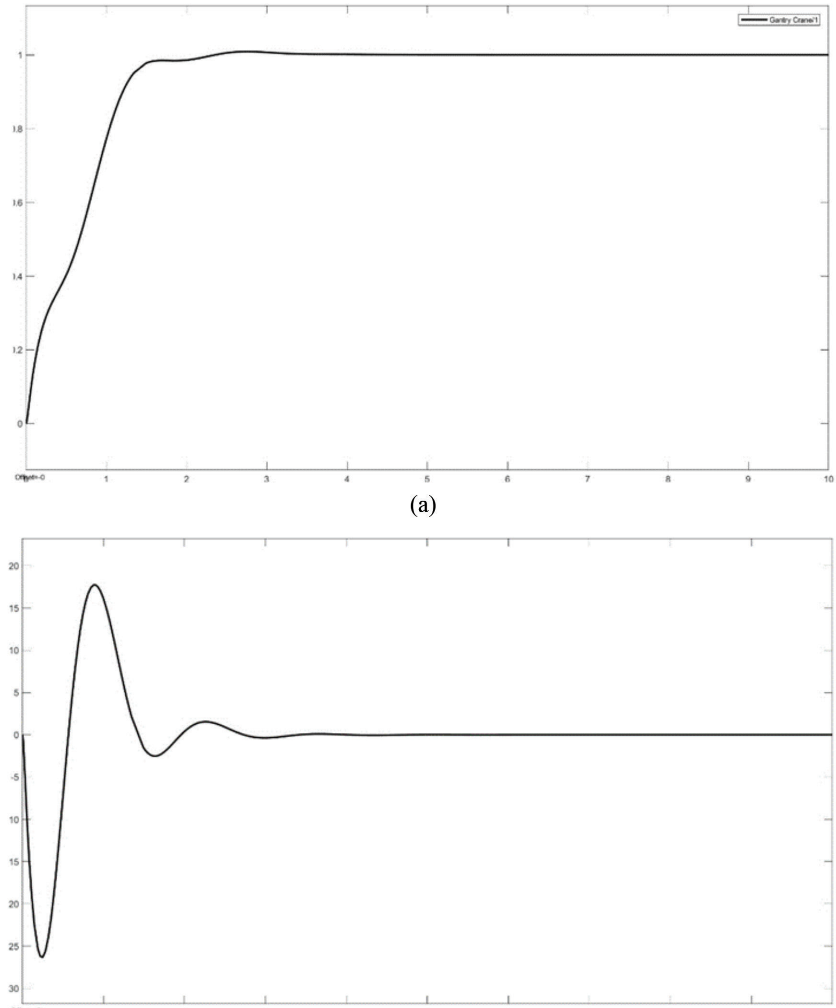
(a)



(b)

Figure 4: System response of (a) trolley position (b) payload ocsillation

in order to find the optimal parameters such as the number of particles of 20, the number of iterations of 50, the upper and lower boundary of the tuning parameters were set to 25 and 0 respectively, except for K_I and K_{DS} which set to 5 and 0 in order to gain the high stability and short transient response of the system. In addition, cognitive and social coefficient (c1 and c2) were set to 1.42. the initial inertia weight was set to 0.9 and lineraly decreased to 0.4, proportional to



(a)

(b)

Figure 5: System response of (a) trolley position (b) payload oscillation

Table 3: Performance indices for the proposed and benchmarking methods

PID-PD controller	Trolley Displacement			Payload Oscillation	
	IAE	**OS (%)**	**T_S (s)**	**θ_{max}**	**T_S (s)**
Automatic PID tuner	1.245	24.375	6.088	31.98°	2.869
PSO	0.7103	0.505	1.727	26.32°	2.437

the number of iteration during the optimization process. The optimization was carried out using Matlab/Simulink.

The simulation results for the trolley position and payload swing responses obtained using automatic PID tuner and PSO methods are shown in Figure 4 and 5 respectively. Table 3 tabulates the performance indices for the proposed and comparative method.

The system response for trolley position in terms of IAE was low as compared to the automatic PID tuner controller. OS and T_S values were very small as compared to the automatic PID tuner controller. System response for payload swing has a smaller T_S and θ_{max} compared to automatic PID tuner controller.

Analyzing the overall response between the proposed method and the comparative method, the proposed method is better than comparative method with improvement of %. One of the reasons the PSO-tuned method is proposed because it can solve any optimization problem efficiently. The optimal parameters can be obtained accurately and give the best system performance in tracking the best trolley position and minimizing the payload swing angle.

Afterwards, it is desirable to test the performance of the proposed PSO-tuned controllers under various payload mass and cable length. First, various payload mass is tested using PSO-tuned controllers with a fixed cable length and vice versa. Payload mass used in this study were 0.2 kg, 0.7 kg, and 1.2 kg with a fixed cable length of 0.5 m. The performance indices of various payload mass of the trolley displacement and the oscillation of payload are shown in Table 4.

The system response obtained for both trolley displacement and payload oscillation are shown in Figure 6. It is noted with different mass variables, the IAE, OS, and T_S of trolley displacement and payload oscillation system response are slightly different. The highest payload mass, 1.2 kg used in this study gave a smallest IAE followed by 0.7 kg and 0.2 kg. It also has the smallest OS compared to 0.7 kg and 0.2 kg. However, it required the highest time to settle. For payload oscillation, 0.2 kg has the least maximum angle but has the highest T_S.

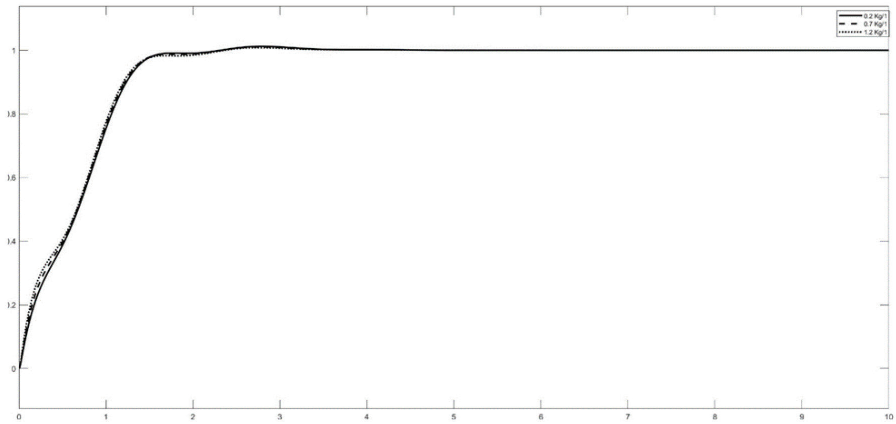
Next, it also desirable to examine the performance of the system response with a various cable length. In this study, the length of cable such as 0.2 m, 0.8 m, and 1.0 m were used in order to verify the proposed algorithm performance. Table 5 tabulates the performance indices for the proposed method with different cable lengths. The system response obtained for various cable length used are shown in Figure 5. The results obtained for the trolley displacement of the system response shows 0.2 m cable length has a smallest IAE while 1.0 m cable length has the highest OS and 0.8 m cable length has the smallest time required for the system response to settle. The payload oscillation system response of 0.2 m cable length has the greatest maximum angle in terms of swing but minimum time was required for the system response to reach a stabilize state.

Conclusions

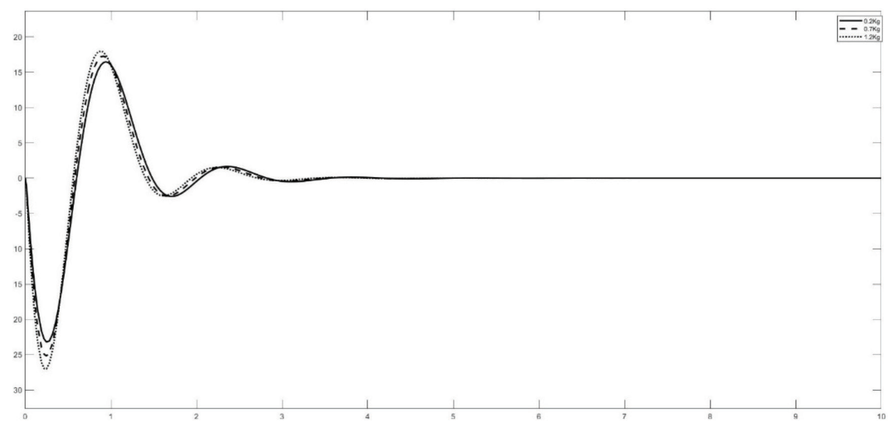
An optimal PID controller with the combination of both PID and PD has been proposed in this paper where the PID controller was utilized for tracking the best trolley position and the PD controller was used for reducing the payload

Table 4: Performance indices with different payload masses

Payload Mass (kg)	Trolley Displacement			Payload Oscillation	
	IAE	OS (%)	T_S (s)	θ_{max}	T_S (s)
0.2	0.7393	1.531	1.522	23.22	2.563
0.7	0.7197	1.531	1.522	25.19	2.483
1.2	0.7048	0.505	1.827	27.02	2.410



(a)



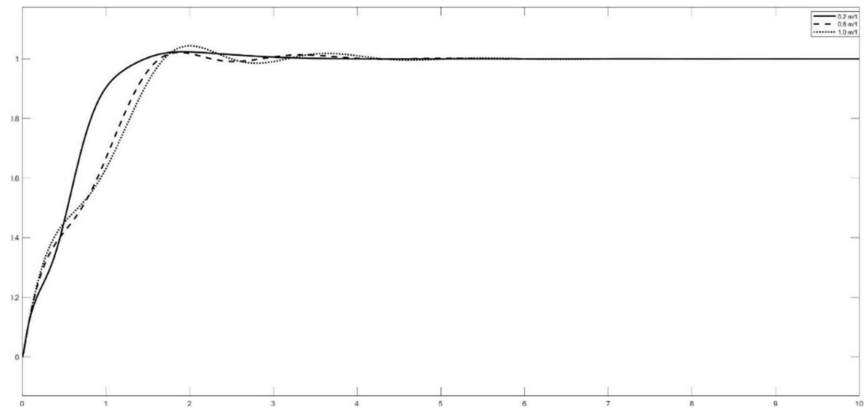
(b)

Figure 6: Sytem response of (a) trolley position (b) payload oscillation: 0.2 kg (solid line), 0.7 kg (dashed line) and 1 kg (dotted line)

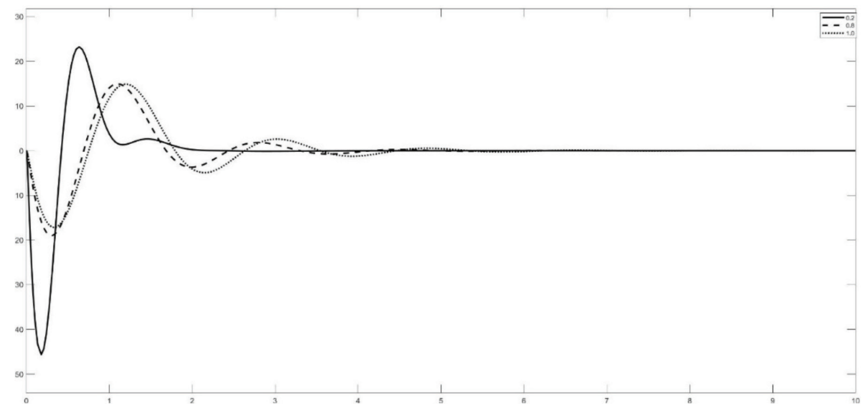
Table 5: Performance indices with different cable lengths

Cable Length (m)	**Trolley Displacement**			**Payload Oscillation**	
	IAE	**OS (%)**	**T_S (s)**	**θ_{max}**	**T_S (s)**
0.2	0.6580	2.577	2.215	45.65	1.768
0.8	0.7864	2.577	1.948	18.99	3.048
1.0	0.8270	4.737	2.293	17.18	4.039

swing angle. PSO was implemented in the system for solving optimization problems for tuning all parameter gains using fitness function method based on the priority approach. All the gains have been evaluated using a control structure that implements PID and PD controllers. Based on the simulation result observed, PSO-tuned controllers parameter are able to move a payload fastly from one point to another without contributing to high payload oscillation.



(a)



(b)

Figure 7: Sytem response of (a) trolley position (b) payload oscillation: 0.2 kg (solid line), 0.7 kg (dashed line) and 1 kg (dotted line)

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