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Optimal Control for a Gantry Crane System Using Priority Fitness Strategy of Particle Swarm Optimization

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ABSTRACT

The basic operating concept of a gantry crane system is to move payloads from one area to another, which requires precise trolley positioning with low payload sway. This paper investigates the impact of particle swarm optimization incorporating a priority fitness strategy in finding the optimal control approach for the gantry crane system. The research contribution of the proposed strategy lies in obtaining optimal proportional-integral-derivative and proportional-derivative control parameters simultaneously under six cases of the system's transient responses, yielding targeted exploration and exploitation for each case and improved robustness across heterogeneous operating conditions. Therefore, a series of transient responses based on overshoot, steady-state error, and settling time are constructed and ranked in every possible configuration to replace the single static priority factor used in the previously developed priority fitness strategy. Interestingly, the simulation results with respective fitness strategies demonstrate the effectiveness of the proposed method. In fact, the trolley moves as fast as possible to the desired position with low payload sway, where Case 2 of the proposed method achieves zero overshoot, zero steady-state error, and a 49.7% improvement in settling time. Through extensive simulations, the proposed strategy also shows consistent performance across various trolley positions and payload masses, highlighting its adaptability and reliability under robust analysis. It is envisaged that the proposed method can be useful for other systems to find the required performances according to the needs and circumstances.

1. Introduction

The gantry crane system is commonly used in industrial environments for lifting and transporting heavy loads along horizontal and vertical axes [1]-[7]. It typically consists of a trolley that moves along a bridge, which itself moves along rails with a suspended payload hanging from a hoist. One of the main challenges in controlling such a system is managing the sway of the payload [8]-[11], which behaves like a pendulum. When the trolley accelerates or decelerates, the payload tends to oscillate, leading to instability and potential safety hazards [12]. Due to its underactuated and nonlinear nature, the gantry crane systems require precise and responsive control strategies to ensure safe and efficient operations, especially during high-speed operations [13]-[16].

One of the most used controllers in such systems is the proportional-integral-derivative (PID) controller. It is favored for its simplicity, ease of implementation, and effectiveness in many industrial applications [17]-[21]. The PID controller adjusts the control input based on the error between the desired and actual positions, integrating past errors and predicting future trends. In gantry cranes, PID controllers are typically used to control the trolley position and hoist movement, although it may struggle with minimizing payload sway under dynamic conditions [22]. Another classical approach is a proportional-derivative (PD) controller, which omits the integral component to reduce overshoot and improve response time. The PD controllers are particularly useful in applications where fast response is critical and steady-state error is less of a concern. In gantry crane systems, PD controllers are often applied to control minimize the sway angle of the payload, as it can provide a quicker damping effect without the risk of integral windup [23]. However, some difficulties still exist in handling the PID or PD controllers, especially in obtaining optimal controller parameters [24]-[34].

Traditional tuning approaches, such as trial and error are suitable for tuning the PID or PD controller parameters. However, this approach relies heavily on the experience and intuition of the crane operator, making it subjective and inconsistent. It lacks a systematic approach and often fails to deliver optimal performance, especially in systems with nonlinear dynamics or varying operating conditions. Another tuning approach is Ziegler-Nichols [18], [35], which is popular due to its simplicity. It provides a more structured method by inducing sustained sways to estimate PID or PD parameters. Unfortunately, the route to discovering the parameters is aggressive, resulting in significant overshoot and oscillatory responses. Given the difficulty in determining the optimal value of PID or PD parameters, several researchers have begun to apply metaheuristic approaches to determine the most appropriate controller parameter values for many systems [36]-[43].

Metaheuristic optimization algorithms have become increasingly popular for tuning PID controllers in gantry crane systems due to their ability to handle complex, nonlinear, and multi-objective problems [22], [44]-[46]. The genetic algorithm (GA), which is based on genetic principles and natural selection, is one of the most used algorithms. GA evolves a population of candidate solutions over multiple generations through operations such as selection, crossover, and mutation. It is especially useful for exploring large and complex search spaces, as it helps to avoid local minimum that can trap traditional optimization methods [47]-[48].

GA has been successfully applied to optimize PID gains in gantry crane systems, often resulting in improved control performance and robustness under varying load conditions and disturbances. Another commonly used method is particle swarm optimization (PSO), which mimics the social behavior of birds flocking to find optimal solutions [45], [49]-[50]. PSO is particularly effective in tuning PID parameters to minimize trolley positioning error and suppress payload swing. Variants fitness function has been developed to reflect control objectives, such as reducing overshoot, settling time, and steady state error that highly suitable for gantry crane applications. While both PSO and GA can optimize PID controllers for gantry crane systems, PSO tends to be the preferred choice due to its faster convergence, simpler implementation, and better adaptability to multiple objective control problems. Its performance has been validated in both simulation and experimental setups, where it consistently outperforms traditional tuning methods and other metaheuristics in minimizing payload sway and achieving precise trolley control.

Unfortunately, a basic fitness function in PSO for tuning PID controllers presents several disadvantages that can limit the effectiveness of the optimization. One major drawback is its tendency to focus on a single performance metric such as minimizing the overshoot, steady-state error or settling time without considering the broader control objectives. In a complex system like a gantry crane system, a single-objective fitness function can lead to imbalanced results. For instance, optimizing for fast positioning alone may inadvertently increase the robustness of the suspended load, compromising system safety and stability. Thus, multiple goals must be achieved simultaneously for accurate trolley positioning, minimal payload swing, and fast response [51]-[55].

However, the proposed priority fitness strategy does not compete with hybrid metaheuristics structure but enhances the fitness evaluation mechanism within the PSO framework. Thus, the three dominant transient responses, namely overshoot, steady-state error, and settling time are prioritized and represent the most practically relevant performance indicators for oscillatory systems such as gantry crane systems, where trolley and sway suppression are primary concerns. In this paper, optimal PID and PD controllers tuned by PSO for the control of a gantry crane system are proposed. The research contributions of this paper can be listed as follows:

1) A priority fitness strategy is constructed and ranked in six possible configurations with different settings of the overshoot, steady-state error and settling time.
2) The controllers with five control parameters are concurrently tuned to ensure optimal performance in the trolley position and the payload sway.
3) Extensive simulations are carried out to further verify the robustness of crane operating conditions under different trolley positions and payload masses.

2. Gantry Crane System

Fig. 1 shows an illustration of a gantry crane system. The trolley mass, the payload mass, the cable length, the trolley horizontal position, the sway angle, the torque and the driving force are represented as m, m_P, l, x, θ, T and F, respectively. There are several methods for modelling and simulating the gantry crane system. According to the findings, the Lagrange equation is better suited for determining the mathematical expression for representing the system [56]-[60]. Some assumptions were made to reduce modelling challenges, such as the cable length being fixed and massless.

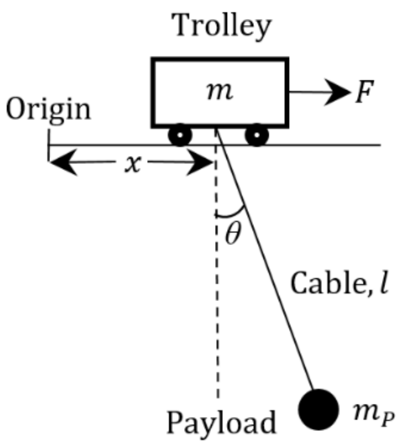


Fig. 1. Illustration of a gantry crane system

The gantry crane system has two independent generalized coordinates: trolley displacement (x) and payload sway (θ). Lagrange's equation is expressed in its standard form as follows [50], [61]:

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

where L, Q_i, and q_i denote the Lagrangian function, nonconservative generalized forces, and independent generalized coordinates. The Lagrangian function can be written as:

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

with T and P represent kinetic and potential energies, respectively. This relationship involved calculating on how it relates to having more flexible coordinates. Kinetic and potential energy can be obtained as:

$$T = \frac{1}{2}\left[(m + m_P)\dot{x}^2 + ml^2\dot{\theta}^2\right] + m\dot{x}\dot{\theta}l\cos\theta \tag{3}$$

$$P = -mgl\cos\theta \tag{4}$$

Thus, the Lagrangian function can be obtained as:

$$T = \frac{1}{2}\left[(m + m_P)\dot{x}^2 + ml^2\dot{\theta}^2\right] + m\dot{x}\dot{\theta}l\cos\theta + mgl\cos\theta \tag{5}$$

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

$$(m + m_P)\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta = F - B\dot{x} \tag{6}$$

$$ml^2\ddot{\theta} + ml\ddot{x}\cos\theta + mgl\sin\theta = 0 \tag{7}$$

Since the dynamic DC motor is incorporated in the model of the gantry crane system to drive the trolley movement, differential equations with their effects are constructed.

$$T_m = J_m\left[\frac{d^2\theta_m}{dt^2}\right] + D_m\left[\frac{d\theta_m}{dt}\right] \tag{8}$$

The moment inertia, J_m is very small yields:

$$T_m = D_m\left[\frac{d\theta_m}{dt}\right] = \frac{T_L}{r} \tag{9}$$

where load torque, T_L and rotor angle position, θ_m can be represented as:

$$T_L = Fr_P \tag{10}$$

$$\theta_m = \frac{r}{r_P}x \tag{11}$$

and V is an input voltage.

$$V = R_i + L\frac{di}{dt} + V_b \tag{12}$$

Since the inductance, L is neglected, then (9), (10) and (11) are substituted into (13).

$$V = Ri + V_b \tag{13}$$

$$V = R\left[\frac{T_m}{K_T}\right] + K_E\left[\frac{d\theta_m}{dt}\right] \tag{14}$$

$$V = R\left[\frac{\frac{T_L}{r}}{K_T}\right] + K_E\frac{d}{dt}\left[\frac{r}{r_P}x\right] \tag{15}$$

$$V = \frac{RFr_P}{K_T r} + \frac{K_E r}{r_P}\dot{x} \tag{16}$$

The equation can be rearranged as:

$$F = \frac{VK_T r}{Rr_P} - \frac{K_E K_T r^2}{R{r_P}^2}\dot{x} \tag{17}$$

A comprehensive equation for the gantry crane system can be constructed by considering the dynamic DC motor as (18) and (19).

$$\left[\frac{RBr_P}{K_T r} + \frac{K_E r}{r_P}\right] + \left[\frac{Rr_P}{K_T r}\right]\left[(m + m_P)\ddot{x} + ml\left[\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta\right]\right] = V \tag{18}$$

$$ml^2\ddot{\theta} + ml\ddot{x}\cos\theta + mgl\sin\theta = 0 \tag{19}$$

Therefore, the control difficulty is achieving a low payload sway angle (θ) during trolley movement. Table 1 shows the simulations' system parameters [61].

3. Control Structure, PSO and Priority Fitness Strategy

This section describes the PID and PD controllers as positive and negative feedback control designs for a gantry crane system. The PID controller is utilized for positioning, whereas the PD controller reduces payload sway. In addition, effective tuning methods using PSO are explored to obtain optimal PID and PD controller parameters simultaneously under six cases of priority fitness strategy. A series of strategies based on overshoot (OS), steady-state error (e_{SS}) and settling time (T_S) is constructed and ranked in every possible configuration.

3.1. PID and PD Controllers

To fulfil both control objectives, namely precise trolley positioning and low payload sway, a control system integrating PID and PD controllers is proposed, as seen in Fig. 2. Thus, five controller parameters must be tuned at the same time. The nonlinear dynamic model of the gantry crane system in (18) and (19) is to be simulated using the PID and PD controller parameters. As tuning both PID and PD controllers to produce optimal system performance is complex, PSO algorithm with a priority fitness strategy is explored and applied to find optimal controller parameters. The exercises are carried out using an 11th Gen Intel(R) Core(TM) i5-1135G7 Processor, 2.4GHz, 8GB RAM, Microsoft Windows 11, MATLAB R2023a and run with the solver of ode45 (Dormand-Prince) with a sampling time of 0.001 s.

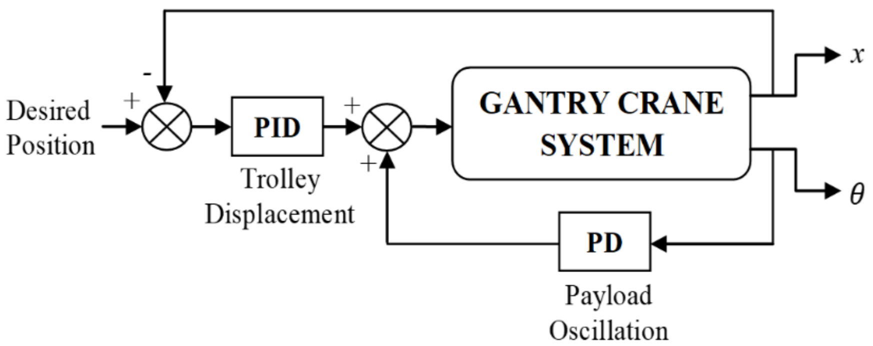


Fig. 2. Control structure with PID and PD controllers

3.2. PSO

Kennedy and Eberhart created the PSO approach, which is still utilized today to tackle a variety of technical challenges [62]-[65]. In PSO, a population of candidate solutions known as particles explores the search space for possible controller parameter values. Each particle adjusts its position in accordance with its own best-known position as well as the swarm's best-known position. The social sharing of knowledge enables the swarm to converge on an optimal or near-optimal solution. In the context of gantry cranes, the fitness function utilized in PSO may include numerous objectives and strategies, such as a priority fitness strategy, to achieve optimal control of the gantry crane.

Table 1. Gantry crane system parameters

Variables	Parameters		
	Symbol	Values	Unit
Trolley Mass	m	5	kg
Payload Mass	m_P	1	kg
Cable Length	l	0.75	m
Resistance	R	2.6	Ω
Radius of Pulley	r_p	0.02	m
Damping Coefficient	B	12.32	Ns/m
Electric Constant	K_E	0.007	Nm/A
Torque Constant	K_T	0.007	Vs/rad
Gravitational Constant	g	9.81	m/s^2
Gear Ratio	r	15	-

The optimization approach involves two initial parameters for the particles: position, x_k^i and velocity, v_k^i. The new particle velocity, v_{k+1}^i is determined by the present x_k^i, local best (P_{best}) and global best (G_{best}) values. The new position, x_{k+1}^i will be changed according to the new velocity as follows:

$$v_{k+1}^i = wv_k^i + c_1 r_1 (P_{best} - x_k^i) + c_2 r_2 (G_{best} - x_k^i) \tag{20}$$

$$x_{k+1}^i = v_{k+1}^i + x_k^i \tag{21}$$

where the number of iterations is denoted by i (i = 1, 2, 3, ……., N). The c_1 and c_2 are positive learning factors that influence the strength of cognitive and social acceleration coefficients, whereas r_1 and r_2 are random function values ($r_1, r_2 \in U(0,1)$). In addition, the P_{best} and G_{best} are the personal best and best position among P_{best}, respectively. The inertia weight (w), which decreases from 0.9 to 0.4 during iterations influences particles exploration and exploitation. In fact, a fitness function evaluates each individual particle. All particles strive to replicate their prior success while also following the success of the best agent. This means that P_{best} and G_{best} are updated at each iteration if the particle has a lower fitness value than the current P_{best} and G_{best}, up to the maximum number of iterations (N). In this situation, the particle location in PSO can be described as:

$$x^i = [K_P, K_I, K_D, K_{PS}, K_{DS}] \tag{22}$$

where K_P, K_I, K_D represent the proportional, integral and derivative values of PID controller used to control the trolley position. In addition, the K_{PS} and K_{DS} are the PD controller's proportional and derivative values for minimizing the payload sway of the gantry crane system that is illustrated in Fig. 3.

3.3. Priority Fitness Strategy

A priority fitness strategy is a modified version of a standard objective function that is used in conjunction with PSO to prioritize the system's transient responses. This enables the algorithm to focus on the most important components of the objective function, potentially leading to more effective solutions. In this work, transient responses such as OS, e_{SS} and T_S is designated as objective function components to be prioritized. Thus, six cases can be investigated to obtain optimal control of the gantry crane system as listed in Table 2.

Table 2. Six cases with different set of priority fitness strategies

Cases	Priority Fitness Strategy		
	OS	e_{SS}	T_S
Case 1	1^{ST}	2^{ND}	3^{RD}
Case 2	1^{ST}	3^{RD}	2^{ND}
Case 3	2^{ND}	3^{RD}	1^{ST}
Case 4	2^{ND}	1^{ST}	3^{RD}
Case 5	3^{RD}	1^{RD}	2^{ND}
Case 6	3^{RD}	2^{ND}	1^{ST}

Table 3 shows the probability of pattern for P_{best} and G_{best} selection with reference to Case 1, which makes it easier to understand. Thus, ten iterations with three sets of situations are provided to display different priority values. The priority fitness strategy with PSO method is employed to identify the P_{best} and G_{best} respectively. For instance, the coordinate of Iteration:2 Situation:1 is selected as P_{best} based on priority at the first stage. This is because it has a smaller OS and the other two criteria are no longer relevant.

Other examples can be explored in Situation 2. In this situation, the smaller value of OS (0.114%) is equal between Iteration 1 and Iteration 3 compared to Iteration 2 (0.137%) and Iteration 10 (0.286%). Thus, the second priority, e_{SS} is immediately liable for taking over instead of OS. The smaller e_{SS} value will be chosen regardless of T_S value. Therefore, Iteration:1 Situation:2 is selected as P_{best}. Moving to Situation 3, the third priority, T_S is responsible for finding the smaller T_S values due to the OS and e_{SS} smaller values are equal between Iterations 2 and 3. Thus, coordinate Iteration:3 Situation:3 is chosen as P_{best}. This process is repeated until the system receives the optimal P_{best} value and the respective P_{best} will be selected as a new G_{best}best solutions. Nevertheless, if the current G_{best} does not produce the best results, the prior G_{best} will remain.

4. Results and Discussion

The proposed method's ability to provide accurate trolley positioning and low payload sway is investigated in the simulated environment of a gantry crane system. In this approach, the PSO with priority fitness strategy is utilized to automatically tune the PID and PD controllers' parameters. The algorithm iteratively explores the parameter space and assigns priorities to different parameter sets according to their fitness values. Six different cases of control parameter values with different sets of priority are presented in Table 4. In this work, the OS, e_{SS} and T_S are also measured for trolley performance. Furthermore, the payload maximum amplitude, θ_{max} angle is measured, as well as the payload sum squared errors, SSE_θ. Low values of θ_m and SSE_θ indicate low sways, which are critical for ensuring the stability and precision of the gantry crane system in real-world operations. This includes extensive simulation to further verify the robustness of efficient hook and payload sway control under different trolley positions and payload masses.

Fig. 4 shows the performance of trolley position and payload sway under Case 1. In this case, the OS is chosen as the first ranking of priority and followed by the e_{SS} as the second priority. In addition, the T_S lies as the third priority. The response depicted a zero OS for the trolley position, which symbolizes the correctness of the priority fitness strategy that prioritizes the OS as the first priority. At the same time, there is zero e_{SS} but it comes with a longer T_S. In terms of payload sway, it reaches a relatively low θ_m and SSE_θ values.

Under Case 2, OS is set as a priority, followed by T_S in second and e_{SS} in third. The gantry crane system response shows a slightly similar response to Case 1, in which the trolley response produces zeros OS as shown in Fig. 5. Even though the e_{SS} is not emphasized in this case, the e_{SS} still can reach zero value. Interestingly, this case shows a faster T_S compared to Case 1 due to the rank of T_S lies on the second priority. In terms of payload sway, it also achieves a relatively low θ_m and SSE_θ values. However, fast T_S slightly affect to the θ_m and SSE_θ values compared to Case 1.

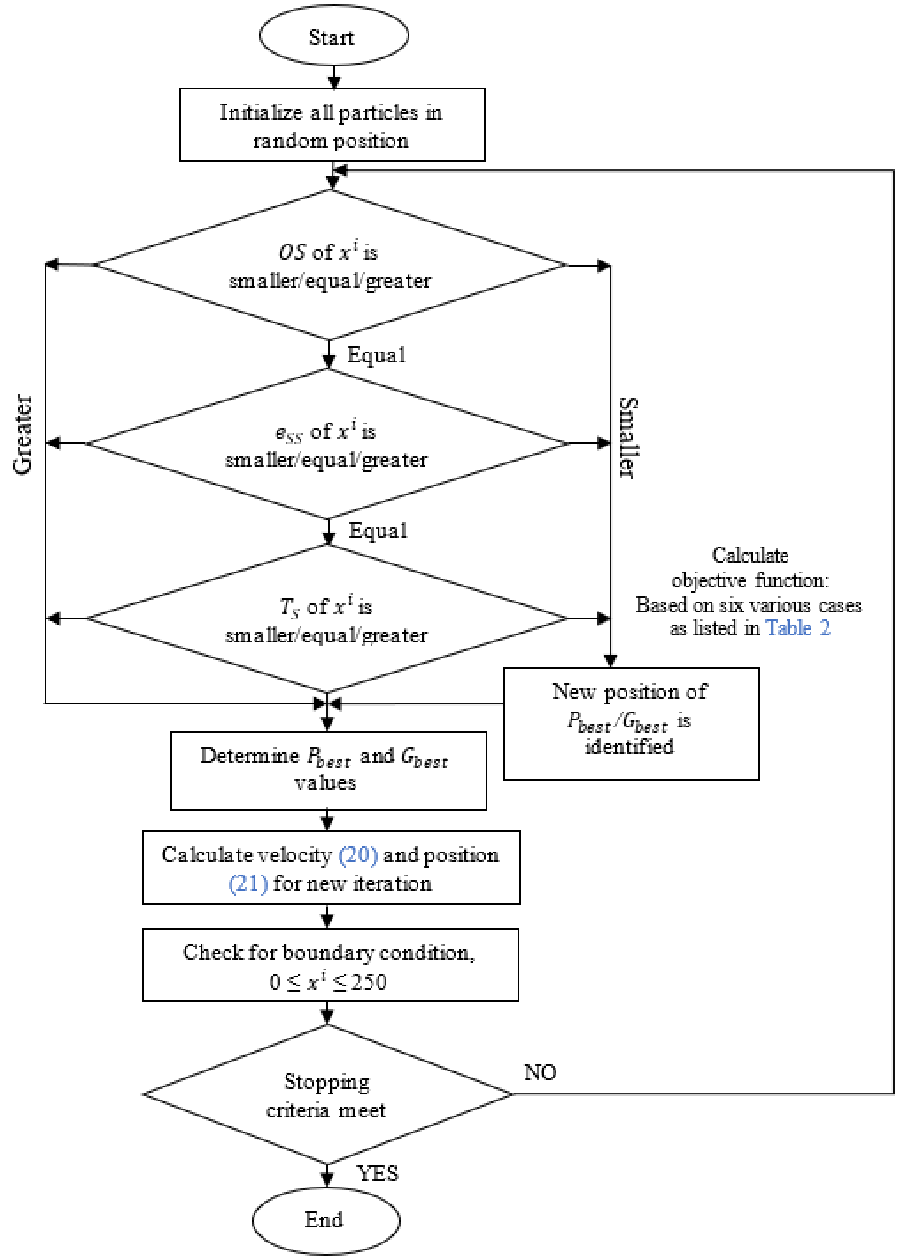
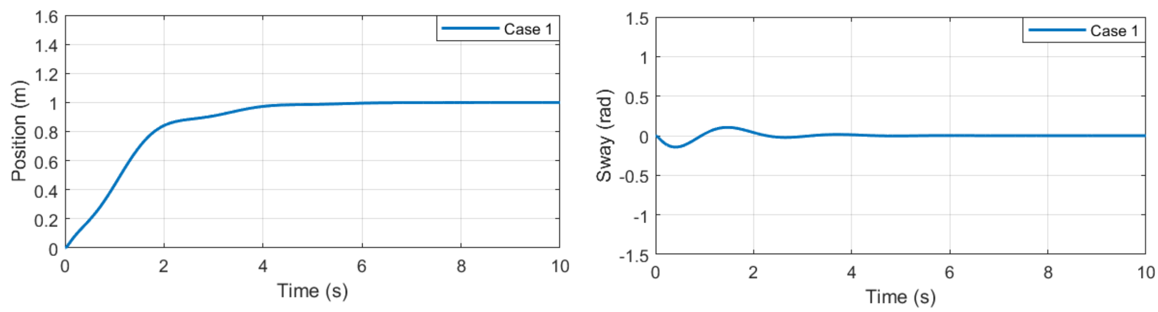


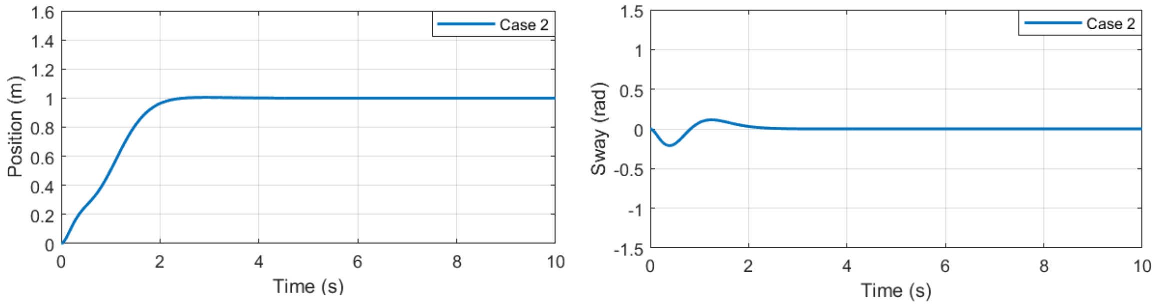
Fig. 3. Concept of new updated position for P_{best}/G_{best} of priority fitness strategy with PSO



(a) (b)

Fig. 4. Case 1: (a) Trolley position (b) Payload sway

In Case 3, the T_S are now the top priority, followed by e_{SS} in second and OS in third. In this situation, the trolley is successfully achieved to the desired position with fast T_S within less than one second. It is clearly observed that a faster T_S resulted in an unstable overall response, with a persistent sway on the trolley position response. Due to this ripple on the trolley, it also affects the payload sway where the θ_m and SSE_θ values are high and continuously oscillate towards the end of the simulation time as shown in Fig. 6. The other three cases are also as plotted in Fig. 7, Fig. 8 to Fig. 9. It successfully provided the results as expected and recorded in Table 5.



(a) (b)

Fig. 5. Case 2: (a) Trolley position (b) Payload sway

Table 3. Probability of pattern for P_{best} and G_{best} selection based on Case 1

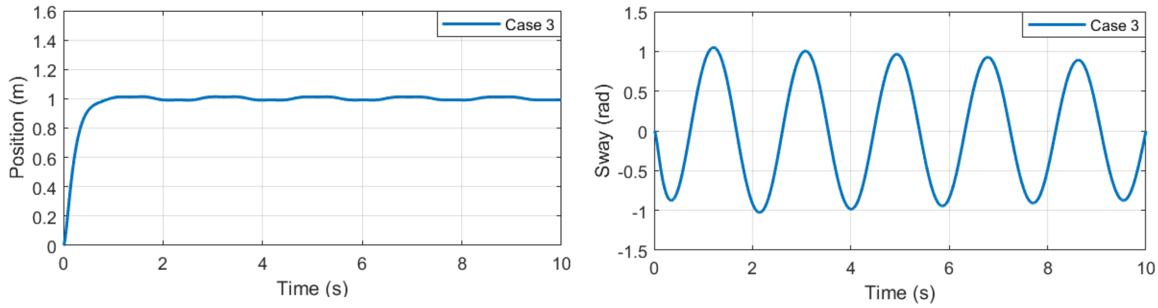
	Priority	Situation 1	Situation 2	Situation 3
	OS (%)	0.157	0.114	0.115
Iteration 1	e_{SS} (m)	0.002	0.001	0.000
	T_S (s)	9.546	9.546	9.546
	OS (%)	0.188	0.137	0.108
Iteration 2	e_{SS} (m)	0.001	0.001	0.000
	T_S (s)	8.385	8.385	7.953
	OS (%)	0.173	0.114	0.108
Iteration 3	e_{SS} (m)	0.002	0.002	0.000
	T_S (s)	7.953	7.953	6.367
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
	OS (%)	0.141	0.286	0.115
Iteration 10	e_{SS} (m)	0.002	0.001	0.002
	T_S (s)	6.817	8.154	8.358
	OS (%)	0.141	0.114	0.108
$\boldsymbol{P_{best}}$	e_{SS} (m)	0.002	0.001	0.000
	T_S (s)	6.817	9.546	6.367
	Iteration: Situation	10:1	1:2	3:3
	SSE (m)	-	-	0.108
Secected$\boldsymbol{G_{best}}$	OS (%)	-	-	0.000
	T_S (s)	-	-	6.367
	Iteration: Situation	-	-	3:3

Table 4. PID and PD controller parameters

Cases	**Parameters**				
	$\boldsymbol{K_P}$	$\boldsymbol{K_I}$	$\boldsymbol{K_D}$	$\boldsymbol{K_{PS}}$	$\boldsymbol{K_{DS}}$
Case 1	45.2557	0.0074	48.9579	105.1899	16.3280
Case 2	25.7033	0.0003	13.4813	51.5767	0.0622
Case 3	249.5494	2.6197	44.1732	0.0346	0.1866
Case 4	125.1931	0.0012	84.7052	197.9454	0.0032
Case 5	52.5428	30.8282	22.1271	66.9782	1.0136
Case 6	246.7848	5.8989	45.9688	0.0114	0.1408

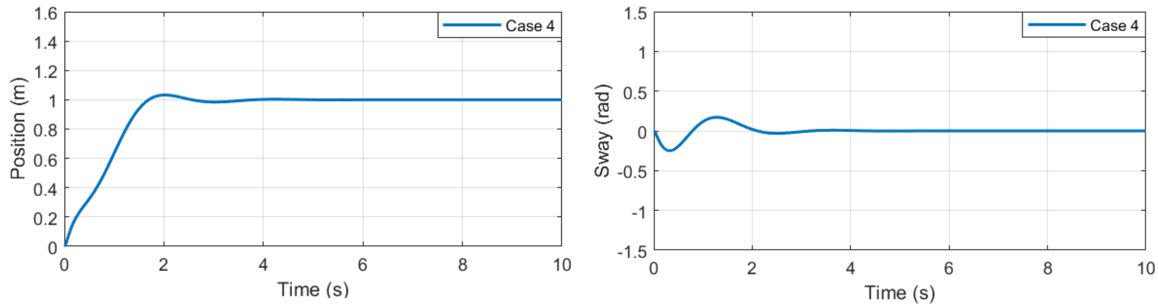
From the overall analysis, it can be observed that Case 2 provides the optimal control performance of the gantry crane system with a distance of 1 m and a payload mass of 1 kg. This selection is made based on the low OS, e_{SS} and T_S. Case 2 is seen to have the lowest OS (0.000%),

e_{SS} (0.000 m) and T_S (2.137 s). Even though Case 1 provides minimum values of θ_m and SSE_θ compared to Case 2, the θ_m and SSE_θ of Case 2 are still accepted because there is no significant difference.



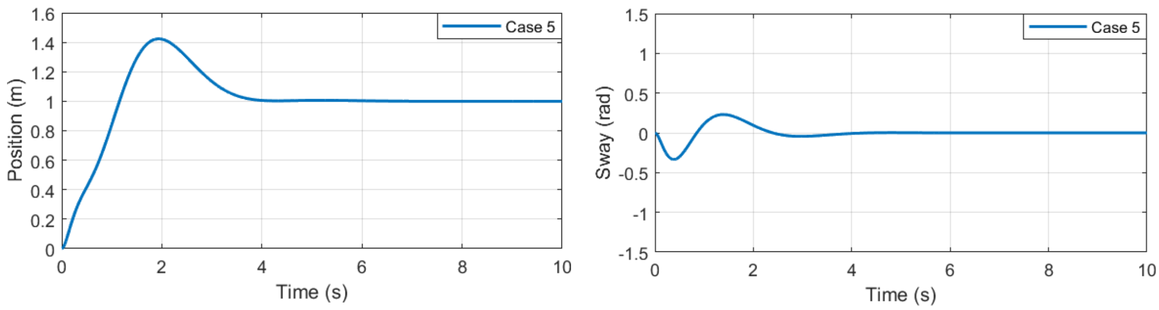
(a) (b)

Fig. 6. Case 3: (a) Trolley position (b) Payload sway



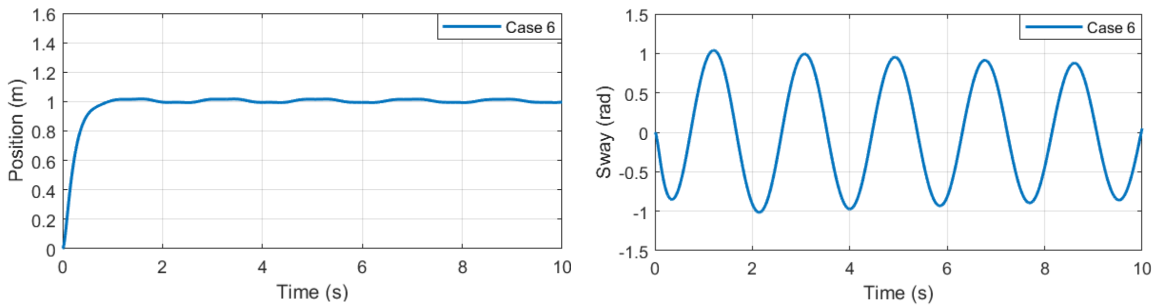
(a) (b)

Fig. 7. Case 4: (a) Trolley position (b) Payload sway



(a) (b)

Fig. 8. Case 5: (a) Trolley position (b) Payload sway



(a) (b)

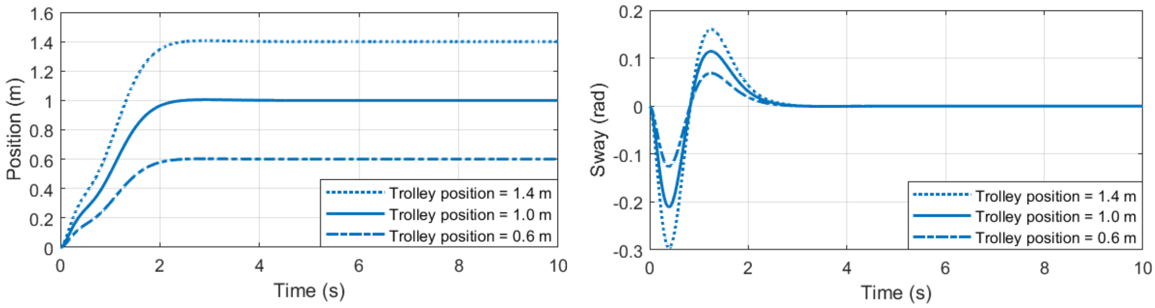
Fig. 9. Case 6: (a) Trolley position (b) Payload sway

As Case 2 is the best optimal tuning strategy, the performance of the gantry crane system with similar control parameters as in Section 3 is then examined under two different robust performances:

(1) various trolley position and (2) various payload mass. Indirectly, it is desirable to investigate the robustness of the controller's performance. With a payload mass of 1 kg, the system responses are successfully tracked to all desired positions with zero OS and e_{SS}, as shown in Fig. 10. However, the T_S is decreasing in relation to the short trolley position distance. In addition, variation in different trolley positions can have an impact on the payload sway. In relation to the distance reduction, the θ_{max} and SSE_θ are decreasing. The simulation results with different trolley positions are summarized in Table 6, which displays the system response at 1.4 m, 1.0 m and 0.6 m, respectively.

Table 5. Performances of each case for trolley position

Cases	Trolley Position			Payload Sway	
	OS (%)	e_{SS} (m)	T_S (s)	θ_{max} (rad)	SSE_θ
Case 1	0.000	0.000	4.246	0.105	1.663
Case 2	0.000	0.000	2.137	0.114	2.421
Case 3	1.400	1.002	0.769	1.049	458.442
Case 4	0.000	0.000	2.290	0.171	4.153
Case 5	42.300	0.000	3.680	0.231	8.164
Case 6	1.800	1.005	0.784	1.039	445.386



(a) (b)

Fig. 10. Various trolley positions

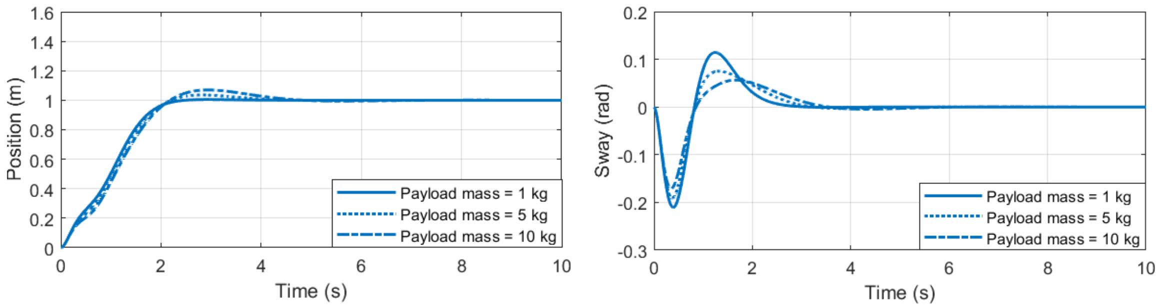
Table 6. Performances of case 2 for various trolley positions

Case 2	Trolley Position			Payload Sway	
	OS (%)	e_{SS} (m)	T_S (s)	θ_{max} (rad)	SSE_θ
1.4 m	0.000	0.000	2.143	0.160	4.782
1.0 m	0.000	0.000	2.137	0.114	2.421
0.6 m	0.000	0.000	2.128	0.069	0.867

Furthermore, the gantry crane system is tested with various payload masses of 1 kg, 5 kg and 10 kg to obtain the necessary trolley position at 1 m. Fig. 11 depicts the system reactions, and it is worth noting that the trolley position response is rather consistent across all loading circumstances. In every condition, zero e_{SS} is reached. In fact, the OS and T_S values are increased with a higher payload mass. However, payload sway responses vary slightly amongst payloads. Higher payload mass leads to lower θ_{max} and SSE_θ values. Simulation results with a higher payload indicate less sway but require longer time to settle down. This is because heavier loads are less responsive to rapid trolley acceleration and increase the system's inertia, which in turn reduces swing amplitude and leads to a longer settling time. Table 7 shows the influence of varying payload masses.

Table 7. Performances of case 2 for various payload masses

Case 2	Trolley Position			Payload Sway	
	OS (%)	e_{SS} (m)	T_S (s)	θ_{max} (rad)	SSE_θ
1 kg	0.000	0.000	2.137	0.114	2.421
5 kg	3.570	0.000	3.546	0.075	1.806
10 kg	6.970	0.000	4.172	0.057	1.370



(a) (b)

Fig. 11. Various payload masses

5. Conclusion

This paper has presented the design of optimal PID and PD controllers for controlling the gantry crane system. The system equations have been derived and used to verify control algorithms, while system responses such as trolley position and payload sway have been thoroughly examined. The optimal controller parameters have been tested based using a control structure that combines PID and PD controllers. In this work, PSO with a priority fitness strategy has been used to find the optimal control parameters. The results clearly demonstrate that the configuration of the fitness strategy significantly influences the performance of the gantry crane system. The proposed method has been validated through simulation studies, and the extensive results indicate that the controller effectively moves the trolley to the required position as fast as possible while minimizing payload sway. Specifically, Case 2 of the proposed method achieved zero overshoot, zero steady-state error, and a 49.7% improvement in settling time. The proposed strategy not only enhances the precision and stability of the system but also offers potential benefits for industrial applications, particularly in improving safety and reducing human intervention during material handling operations. Future research will focus on incorporating rise time into the priority fitness strategy, integrating it with other control structures or metaheuristic optimization techniques, and evaluating its performance on various systems. Furthermore, experimental implementation will be considered to verify its effectiveness under real-world conditions.

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