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Controller design for gantry crane system using modified sine cosine optimization algorithm

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ABSTRACT

The objective of this research paper is to design a control system to optimize the operating works of the gantry crane system. The dynamic model of the gantry crane system is derived in terms of trolley position and payload oscillation, which is highly nonlinear. The crane system should have the capability to transfer the material to destination end with desired speed along with reducing the load oscillation, obtain expected trolley position and preserving the safety. Proposed controlling method is based on the proportional-integral-derivative (PID) controller with a series differential compensator to control the swinging of the payload and the system trolley movement in order to perform the optimum utilization of the gantry crane. Standard sine cosine optimization algorithm is one of the most-recent optimization techniques based on a stochastic algorithm was presented to tune the PID controller with a series differential compensator. Furthermore, the considered optimization algorithm is modified in order to overcome the inherent drawbacks and solve complex benchmark test functions and to find the optimal design's parameters of the proposed controller. The simulation results show that the modified sine cosine optimization algorithm has better global search performance and exhibits good computational robustness based on test functions. Moreover, the results of testing the gantry crane model reveal that the proposed controller with standard and modified algorithms is effective, feasible and robust in achieving the desired requirements.

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1. INTRODUCTION

Gantry cranes are the kind of crane that suspend loads by a steel wire. The wire is linked in a trolley that moves horizontally on the rails. Gantry cranes are extensively used for transferring heavy loads in many places such as construction sites, water treatment plants, power stations, and sea ports' shipping. The operation of the cranes can be divided into five stages: gripping the material, lifting the load, moving the payload from one place to another place, lowering the steel wire and dropping the material. Transferring the load from a point to destination point is time consuming task and requires a highly practiced operator to perform this specific job [1]. The gantry crane suffering from the load swing and an accuracy of the desired position, which are very interesting research area to prevent the accident occurring due to the operators' errors and the transfer speed of the heavy materials, which may lead for load sway. Finally, these conditions may drive the gantry crane to be unstable and causing the collapse with harm to the individuals and properties.

Many attempts for controlling the gantry crane system have been applied in the literature to reducing the oscillation angle and stabilize the trolley of the crane and finally achieving the design requirements. The authors in [2], controlled an automatic gantry crane by the proportional-integral-derivative (PID) controller tuned by a particle swarm optimization (PSO) algorithm to find out the optimal PID parameters with minimum-maximum optimization. J. Smoczek and J. Szpytko in [3], handle the load deviation from the vertical axis of the crane system using a Takagi-Sugeno-Kang (TSK) neuro-fuzzy controller to achieve the desired position with taking under consideration the precision, rope length and load mass. Developing a PID controller with improved PSO algorithm using a priority-based fitness method is implemented in [4], to control the position and oscillation of the gantry crane system. The researchers in [5], developed a combination of PID-PI controller for the crane system to minimize the pendulum-like settings which caused many difficulties and dangerous conditions with new performance criterion function that used to tune the PID-PD controller using PSO algorithm. X. Shao *et al.* [6], proposed a Takagi-Sugeno (T-S) fuzzy modeling and robust Linear Quadratic Regulator (LQR) based PSO algorithm for positioning and anti-swing control for the system.

Optimization technique is the routine of making something better through finding the semi-optimal solution for a problem to perform certain objectives by trying variations on an initial solution and using the gained data to get the global optimum [7]. The stochastic swarm-based optimization algorithms have become as a research interest to many researchers due to their ability to provide low cost, fast, feasible and reasonably precise solutions for the complex constrained problems. Several algorithms have been developed in order to solve a vast range of problems. In recent years, the standard sine cosine optimization (SSCO) algorithm is found to be one of the successful algorithms and has demonstrated great effectiveness in both critical factors of convergence rate and capability in avoiding local optima and achieving global optima. It was proposed by S. Mirjalili [8], in the year 2016, inspired by the cyclic pattern of the sine and cosine trigonometric function to allow a solution to be re-positioned around another solution. The SSCO algorithm was applied on the several optimization problems appeared in the literature such as automatic generation controller of multi-area thermal system [9], solving of global optimization and structure engineering design problems [10], solution of economic/ecological emissions load problems [11], designing truss structures through discrete sizing and optimization [12].

The performance of the population-based algorithms is examined through checking its power to find a proper trade-off between exploration and exploitation. Where the algorithm has a weak balance between exploration and exploitation be more probably to trap in the local optima, premature convergence and stagnation [13]. Depending on the above regards, in this paper, a novel modified sine cosine optimization (MSCO) algorithm is proposed to enhance the exploration and exploitation features in order to improve the solution vectors. Additionally, the developed algorithm is used to adapt the convergence rate and the quality of the PID controller with a series differential compensator (PIDC) tuning. The rest of paper is organized as follows. Next section describes the gantry crane nonlinear model in details. Section 3 introduces the theoretical basics of PIDC controlling method and the SSCO algorithm. The proposed modified algorithm is presented in details in section 4. Subsequently, the tuning of the PIDC controller and the proposed objective function are explained in section 5. The testing of the proposed algorithm's performance and the simulation results are presented in section 6. Finally, general conclusions are drawn in the last section.

2. GANTRY CRANE SYSTEM MODEL

The gantry crane system, shown in Figure 1, is an inherently nonlinear and unstable system which can be considered as an important benchmark system for testing the proposed controlling scheme and optimization algorithm [14]. The Lagrange's equation is the most convenient tool that used to derive the gantry crane model. The gantry crane system depends mainly on three variables namely, the trolley displacement from a reference position $x(t)$, the payload swing angle $\theta(t)$, and the steel wire elongation $\ell(t)$. The dynamics of the system is given as follows [5, 15-17]:

The trolley and payload position vectors are given by,

$$\left.\begin{aligned} \vec{r}_t &= \{x\,,0\} \\ \vec{r}_\ell &= \{x+\ell\,\sin\theta\,,\text{-}\,\ell\,\cos\theta\,\} \end{aligned}\right\} \tag{1}$$

where $x_t = x, y_t = 0, x_\ell = x + \ell\,\sin\theta$, and $y_\ell = \text{-}\,\ell\,\cos\theta$. The kinetic energy of the system is,

$$K_E = \frac{1}{2}(\,m_1\,v_t^2 + m_2\,v_\ell^2) \tag{2}$$

Hence, $v_t^2 = (\dot{x}_t)^2 + (\dot{y}_t)^2 = \dot{x}^2$ (3)

and $v_\ell^2 = (\dot{x}_\ell)^2 + (\dot{y}_\ell)^2 = \dot{x}^2 + 2\,\dot{x}\ell\,\dot{\theta}\,\cos\theta + \ell^2\,\dot{\theta}^2 + 2\,\dot{x}\,\dot{\ell}\,\sin\theta + \dot{\ell}^2$ (4)

Accordingly substitute as shown in (3) and (4) to (2), yields,

$$K_E = \frac{1}{2}(m_1\,\dot{x}^2 + m_2\left(\dot{x}^2 + 2\,\dot{x}\ell\,\dot{\theta}\,\cos\theta + \ell^2\,\dot{\theta}^2 + 2\,\dot{x}\,\dot{\ell}\,\sin\theta + \dot{\ell}^2\right)) \quad (5)$$

and the potential energy of the system is,

$$P_E = -m_2\,g\,\ell\,\cos\theta \quad (6)$$

The nonlinear dynamics of the gantry crane system is modeled bellow using Lagrangian method,

$$L = K_E - P_E = \frac{1}{2}(\,m_1\,\dot{x}^2 + m_2\left(\dot{x}^2 + 2\,\dot{x}\ell\,\dot{\theta}\,\cos\theta + \ell^2\,\dot{\theta}^2 + 2\,\dot{x}\,\dot{\ell}\,\sin\theta + \dot{\ell}^2\right)) + m_2\,g\,\ell\,\cos\theta \quad (7)$$

Now, using Lagrange's equations,

For displacement, x, $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) - \frac{\partial L}{\partial x} = F_t - b\,\dot{x}$ (8)

$$\Rightarrow \frac{\partial L}{\partial \dot{x}} = m_1\dot{x} + m_2\,\dot{x} + m_2\,\ell\,\dot{\theta}\,\cos\theta + m_2\,\dot{\ell}\,\sin\theta$$

$$\Rightarrow \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial \mathrm{L}}{\partial \dot{\mathrm{x}}}\right) = m_1\ddot{x} + m_2\ddot{x} - m_2\,\ell\,\dot{\theta}^2\sin\theta + m_2\,\ell\,\ddot{\theta}\cos\theta + 2\,m_2\dot{\ell}\,\dot{\theta}\cos\theta + m_2\ddot{\ell}\,\sin\theta$$

$$\Rightarrow \frac{\partial L}{\partial x} = 0$$

Therefore, displacement equation can be formulated as follows,

$$(m_1 + m_2)\,\ddot{x} - m_2\,\ell\,\dot{\theta}^2\sin\theta + m_2\,\ell\,\ddot{\theta}\cos\theta + 2\,m_2\dot{\ell}\,\dot{\theta}\cos\theta + m_2\ddot{\ell}\,\sin\theta = F_t - b\,\dot{x} \quad (9)$$

For swing angle, θ, $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = I\ddot{\theta} + c\dot{\theta}$ (10)

$$\Rightarrow \frac{\partial L}{\partial \dot{\theta}} = m_2\dot{x}\,\ell\,\cos\theta + m_2\ell^2\,\dot{\theta}$$

$$\Rightarrow \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) = -\,m_2\ell\,\dot{x}\,\dot{\theta}\sin\theta + m_2\dot{x}\,\dot{\ell}\,\cos\theta + m_2\ddot{x}\,\ell\,\cos\theta + m_2\ell^2\,\ddot{\theta} + 2\,m_2\ell\dot{\ell}\dot{\theta}$$

$$\Rightarrow \frac{\partial L}{\partial \theta} = -\,m_2\ell\,\dot{x}\,\dot{\theta}\sin\theta + m_2\dot{x}\,\dot{\ell}\,\cos\theta - m_2\,\mathrm{g}\,\ell\,\sin\theta$$

Therefore, swing angle equation can be represented as follows,

$$m_2\ddot{x}\,\ell\,\cos\theta + m_2\ell^2\,\ddot{\theta} + 2\,m_2\ell\dot{\ell}\dot{\theta} + m_2\,\mathrm{g}\,\ell\,\sin\theta = I\ddot{\theta} + c\dot{\theta} \quad (11)$$

where m_1 and m_2 are the mass of the trolley and the payload respectively; v_t and v_ℓ are the speed of the trolley and the payload respectively; g is the gravitational acceleration, F_t is the actuating force acted on the trolley, b and c are viscous friction coefficient with the rail and due to pendulum axis respectively; I is the moment of inertia of the payload.

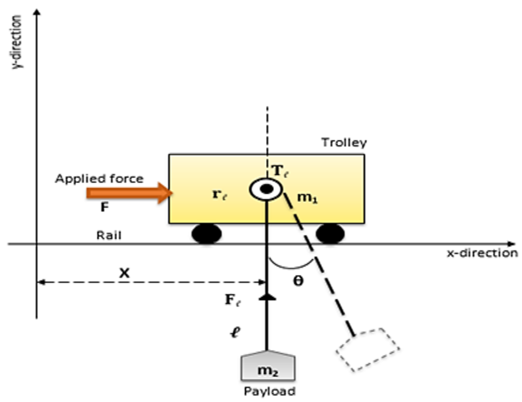


Figure 1. Gantry crane system

Ultimately, as shown in (9) and (11) represent the nonlinear model of the system due to the terms of trigonometric functions and the quadratic terms. In this study, it is assumed that the tension force of the hoisting steel wire that causes the cable elongation has a small effect, which can be neglected, thus the length of the cable is considered to be constant and hence, substitute $\dot{\ell} = \ddot{\ell} = 0$ as shown in. (9) and (11).

3. THEORETICAL BASICS
3.1. PIDC scheme

PID controller was classified as the second contribution of 20th century in the field of instruments, right behind microprocessor, decision and communications. Recently, additional adaptations for the systems have controlled loops in terms of performance, and robustness can be obtained. One of these modifications is merging the PID controller with the series differential compensator to form the PIDC controller to improve the robustness in comparison with the conventional PIDC compensator [18]. The tuning parameters of a PIDC controller are: second order derivative gain proportional gain K_h, derivative gain K_d, proportional gain K_p, integral gain K_i and filter time constant T_f. The transfer function of the PIDC controller is described as shown in (12) below and the gantry crane system with trolley and anti-sway PIDC controllers is depicted in Figure 2.

$$G_{PIDC}(S) = \frac{K_h\, S^3 + K_d\, S^2 + K_p\, S + K_i}{0.5\, T_f^2\, S^3 + T_f\, S^2 + S} \quad (12)$$

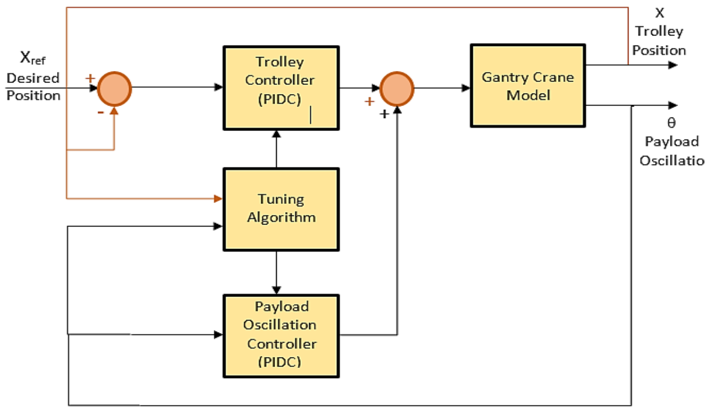


Figure 2. Proposed controlling scheme for gantry crane system

3.2. SSCO algorithm

The SSCOA as previously mentioned is an optimization technique invented by S. Mirjalili [8]. The fundamental characteristic of the SSCO algorithm is that the algorithm's procedure is slightly simple mechanism where the design variable is updated using only the mathematical modeling of the sine cosine functions to guide the population to search for global optimal solutions. In SSCO algorithm, the position's updating rule of an agent's population in the design space is formulated in accordance to the following equation [19-21]:

$$X_{i,j}^{t+1} = \begin{cases} X_{i,j}^t + r_1 \times \sin(r_2) \times \left| r_3 P_j^t - X_{i,j}^t \right| , r_4 < 0.5 \\ X_{i,j}^t + r_1 \times \cos(r_2) \times \left| r_3 P_j^t - X_{i,j}^t \right| , r_4 \geq 0.5 \end{cases} \quad (13)$$

where,
$X_{i,j}^t$: is the position of the current solution in ith search agents at tth iteration and for jth dimension.
n : is the number of the search agents.
D : is the dimension size of the considered problem.
r_1: is a random number in $[a, 0]$.
r_2: is a random number in $[0, 2\pi]$.
r_3: is a random number in $[0,2]$.
P_j^t: is the position of the destination point in jth dimension at tth iteration.
$|\ \ |$: indicates the absolute value.
r_4 : is a random number in $(0,1)$.

$$r_1 = a - t\,\frac{a}{T} \tag{14}$$

where,
t : is the current iteration.
T : is the maximum number of iterations.
a : is a constant and equal to 2.
The steps of the standard sine cosine algorithm are summarized in Algorithm 1:

Input: Population size n, the maximum no. of generations T, the dimension size D, the upper and lower bound of each dimension, the constant a;

Output: The global optima P_j^*;

Start:
1. Generate the initial population within the lower and upper bound for each dimension space;
2. Determine the objective function values and specify the best solution P for the initial population;
3. for $t = 1$ to T
4. calculate r_1 using Eq. (14);
5. for $i = 1$ to n
6. for $j = 1$ to D
7. Generate the values of algorithm's controlling parameters r_2, r_3 & r_4;
8. Update the agents' position using Eq. (13);
9. end for
10. Determine the new objective function based on newly generated agents' position for each dimension;
11. if $OF(X_{i,j}^t) < OF(P_j^{t-1})$
12. Then $X_{i,j}^t = P_j^t$;
13. end if
14. end for

Algorithm 1. The standard sine cosine algorithm

4. MSCO ALGORITHM

The SCO algorithm can disclose proficient accuracy in comparison with other well-known nature-inspired optimization algorithms; it is not qualified for very complex problems and is still may face the difficulty of becoming trapped in local optima [21, 22]. The modified algorithm is proposed to overcome these shortcomings and to step-up its search capability for solving different real-life problems. In this paper, the improvements involved in the MSCO algorithm yielded by the following three directions. Firstly, the inserting of $(2)^{-r_1}$ in the sine and cosine update equations, and by the logarithmic decreasing of the control parameter r_1^t to accelerate the transition from local exploitation to global exploration ability. This idea comes from the fact that the larger value r_1^t can enhance the global searching capability of the algorithm, and the smaller value r_1^t can strengthen the local development power of the algorithm [23]. Secondly, dynamic changing ${r_2}_{i,j}^t$ for each iteration, individuals and dimension will guide the algorithm to jump out from the local optimum which; therefore, efficiently avoids the algorithm premature convergence and enhances the searching precision. Third improvement direction is accomplished by changing ${r_3}_{i,j}^t$ sinusoidally to prevent the MSCO algorithm's population individuals to be alternate in the end of the search process which leads to minimize the number of iterations required. The modifications made in the SSCO algorithm are expressed in the following equations:

$$X_{i,j}^{t+1} = \begin{cases} X_{i,j}^t + (2)^{-r_1} \times \sin(r_2) \times \left| r_3 P_j^t - X_{i,j}^t \right| & , r_4 < 0.5 \\ X_{i,j}^t + (2)^{-r_1} \times \cos(r_2) \times \left| r_3 P_j^t - X_{i,j}^t \right| & , r_4 \geq 0.5 \end{cases} \tag{15}$$

$$r_1^t = a \times (\log_{10} T - \log_{10} t) \tag{16}$$

$$ {r_2}_{i,j}^t = 2\pi \times rand\ (0, 1) \tag{17}$$

$$r_{3\,i,j}^{\,t} = 2 \times \sin(\frac{t}{T} \times \frac{\pi}{2}) \quad (18)$$

$$r_{4\,i,j}^{\,t} = rand\ (0, 1) \quad (19)$$

5. TUNING OF CONTROLLING SCHEMES

5.1. PIDC controller tuning

In this paper presents an effective design method of PID controller with series differential compensator. The boundary values for the tuning parameters of a PIDC controller for both trolley and payload oscillation; K_h , K_d, K_p, K_i and T_f , they are fine-tuned within the range given below,
For trolley controller,
$Lower\ bound =$ [100, 1, 1, 0, 1];
$Upper\ bound =$ [800, 70, 70, 10, 10].
For payload oscillation controller,
$Lower\ bound$ = [30, 0.5, 1, -1, 3];
$Upper\ bound$ = [1300, 50, 55, 10, 20].

5.2. Proposed objective function

The performance index for trolley position and payload oscillations outputs is as follows,

$$J = \alpha\ (P.O + E_{ss}) + \beta\ (t_s - t_r) + \gamma\ ISE + \delta\ MSE \quad (20)$$

where, α, β, γ and δ are weighting factors and $\alpha + \beta + \gamma + \delta = 1$, let $\alpha = \beta = \gamma = \delta = \frac{1}{4}$. ISE stand for integral of the square value of the error & MSE stand for mean square error.

6. RESULTS AND DISCUSSIONS

6.1. Simulation setup

All the experiments in this paper have been conducted on a personal PC with an Intel (R) Core (TM) i7-6500U CPU@ 2.50 GHz processor with 8 GB RAM and 64-bit for Microsoft Windows 10 Pro operating system. The source code has been implemented using MATLAB (R2014a). The gantry crane model and optimization algorithm parameters used through the numerical simulations are obtained from the practical system's data sheet and from the literature, respectively, as listed in Table 1.

Table 1. Parameters' setting for the system model and optimization-algorithms

Parameter	Value
m_1	5 Kg
m_2	1 Kg
ℓ	0.75 m
g	9.81 m/sec^2
b	12.32 $N\ sec/m$
c	0.5 $N\ sec/m$
I	0.03 Kg m^2
T	500 *for MSCOA* 850 *for SSCOA*
n	25
D	20 *for the test functions* 10 for *tuning the PIDC controller*
a	2

6.2. Characteristics of the test functions

In this research work, 14 test functions are taken from the literature [8, 24-26], to investigate the performance of the proposed MSCO algorithm. These problems consist of unimodal, highly complex multimodal and extremely complex composite benchmark functions. The details of the chosen test functions are demonstrated in Table 2.

Table 2. Test functions' details

Function	Type	Scope	Optimum
$f_{01}(x) = \sum_{i=1}^{D} x_i^2$	Unimodal	$[-100, 100]^D$	0
$(x) = \sum_{i=1}^{D} \lvert x_i \rvert + \prod_{i=1}^{D} \lvert x_i \rvert$	Unimodal	$[-10, 10]^D$	0
$(x) = \sum_{i=1}^{D} \left(\sum_{j=1}^{i} x_j\right)^2$	Unimodal	$[-100, 100]^D$	0
$(x) = \max_i\{\lvert x_i \rvert, 1 \leq i \leq D\}$	Unimodal	$[-100, 100]^D$	0
$(x) = \sum_{i=1}^{D} [i x_i^4 + random(0,1)]$	Unimodal	$[-1.28, 1.28]^D$	0
$(x) = \sum_{i=1}^{D} [x_i{}^2 - 10\cos(2\pi x_i) + 10]$	Multimodal	$[-5.12, 5.12]^D$	0
$(x) = -20exp\left(-0.2\sqrt{\frac{1}{D}\sum_{i=1}^{D} x_i{}^2}\right) - exp\left(\frac{1}{D}\sum_{i=1}^{D}\cos(2\pi x_i)\right) + 20 + e$	Multimodal	$[-32, 32]^D$	0
$(x) = \frac{1}{4000}\sum_{i=1}^{D} x_i{}^2 - \prod_{i=1}^{D}\cos\left(\frac{x_i}{\sqrt{i}}\right) + 1$	Multimodal	$[-600, 600]^D$	0
$(x) = \frac{\pi}{D}\{10\sin^2(\pi y_1) + \sum_{i=1}^{D-1}(y_i - 1)^2[1 + 10\sin^2(\pi y_{i+1})] + (y_D - 1)^2\}$ $+ \sum_{i=1}^{D} u(x_i, a, k, m)$ where, $= 1 + \frac{x_i+1}{4}$, $u(x_i, a, k, m) = \begin{cases} k(x_i - a)^m & x_i > a \\ 0 & -a < x_i < a \\ k(-x_i - a)^m & x_i < -a \end{cases}$ $= 10, k = 100$ & $m = 4$.	Multimodal	$[-50, 50]^D$	0
$(x) = 0.1\{\sin^2(3\pi x_1) + \sum_{i=1}^{D}(x_i - 1)^2[1 + \sin^2(3\pi x_i + 1)] + (x_D - 1)^2 [1 +$ ${}^2(2\pi x_D + 1)]\} + \sum_{i=1}^{D} u(x_i, a, k, m)$ where, $x_i, a, k, m) = \begin{cases} k(x_i - a)^m & x_i > a \\ 0 & -a < x_i < a \\ k(-x_i - a)^m & x_i < -a \end{cases}$ $= 5, k = 100$ & $m = 4$.	Multimodal	$[-50, 50]^D$	0
$f_{11}\ (cf_1)$: $f_1, f_2, f_3, \ldots\ldots f_{10} = Sphere's\ Function\ (f_{01}(x))$ $[\sigma_1, \sigma_2, \sigma_3, \ldots\ldots \sigma_{10}]$=[1, 1, 1,…1] $[\lambda_1, \lambda_2, \lambda_3, \ldots\ldots \lambda_{10}]$=[5/100, 5/100, 5/100,…5/100]	Composite	$[-5, 5]^D$	0
$f_{12}\ (cf_2)$: $f_1, f_2, f_3, \ldots\ldots f_{10} = Griewank's\ Function\ (f_{08}(x))$ $[\sigma_1, \sigma_2, \sigma_3, \ldots\ldots \sigma_{10}]$=[5/100, 5/100, 5/100,…5/100] $[\lambda_1, \lambda_2, \lambda_3, \ldots\ldots \lambda_{10}]$=[1, 1, 1,…1]	Composite	$[-5, 5]^D$	0
$f_{14}\ (cf_4)$: $f_1, f_2 = Rastrigin's\ Function\ (f_{06}(x))$ $f_5, f_6 = Griewank's\ Function\ (f_{08}(x))$ $f_7, f_8 = Ackley's\ Function\ (f_{07}(x))$ $f_9, f_{10} = Sphere's\ Function\ (f_{01}(x))$ $[\sigma_1, \sigma_2, \sigma_3, \ldots\ldots \sigma_{10}]$=[1, 1, 1,…1] $[\lambda_1, \lambda_2, \lambda_3, \ldots\ldots \lambda_{10}]$=[1/5, 1/5, 5/0.5, 5/0.5, 5/100, 5/100, 5/32, 5/32, 5/100, 5/100]	Composite	$[-5, 5]^D$	0

6.3. Proposed algorithm assessment

The stochastic nature of the standard and proposed SSCO algorithm is with semi-random staring, that mean the initialization process is different, and the paths followed are dissimilar. To address these differences and to testify the feasibility, convergence and accuracy of the algorithms clearly, each algorithm is evaluated by applying the optimization routine thirty times for each of the fourteen benchmark functions, where five of which are unimodal, five of which are multimodal and four of which are composite. The collected numerical results based on statistical calculations were saved in Microsoft excel file. This operation was performed to determine the average best-so-far (AB) solution and standard deviation (SD) based on the saved excel file and reported in Table 3. It is clear that from the results summarized in Table 3, the proposed algorithm performs quite well in terms of finding the global optima and with a fast-computational time for the selected test functions. Each function was executed instantaneously on a modern laptop, which mean the computing time for 500 iterations taken approximately 2 seconds.

The results indicated the predominance of MSCO algorithm through the capability to achieve the best optimum value in 29 out of 30 runs with a reasonable convergence speed. These solutions prove that the modified approach has excellences in terms of exploration and exploitation. Finally, from the above observations and from the convergence curves depicted in Figure 3, it is worth mentioning that the MSCO algorithm has more competitive accomplishment compared with SSCO algorithm that required 850 generations to reach around 60% of the modified algorithm's best solutions.

Table 3. Statistical assessment for the standard and proposed algorithms

Function	SSCOA		MSCOA	
	AB	SD	AB	SD
f_{01}	0.0000	0.0000	0.0000	0.0000
f_{02}	0.0000	0.0001	0.0000	0.0000
f_{03}	0.0371	0.1372	0.0001	0.0003
f_{04}	0.0965	0.5823	0.0001	0.0004
f_{05}	0.0000	0.0014	0.0000	0.0003
f_{06}	0.0000	0.7303	0.0000	0.0000
f_{07}	0.3804	1.0000	0.0000	0.0000
f_{08}	0.0000	0.0051	0.0000	0.0022
f_{09}	0.0000	0.0000	0.0000	0.0000
f_{10}	0.0000	0.0000	0.0000	0.0000
f_{11}	0.0230	0.0676	0.0007	0.0004
f_{12}	0.0497	0.4921	0.0000	0.0000
f_{13}	0.0000	0.1105	0.0000	0.0018
f_{14}	0.0129	0.0134	0.0122	0.0130

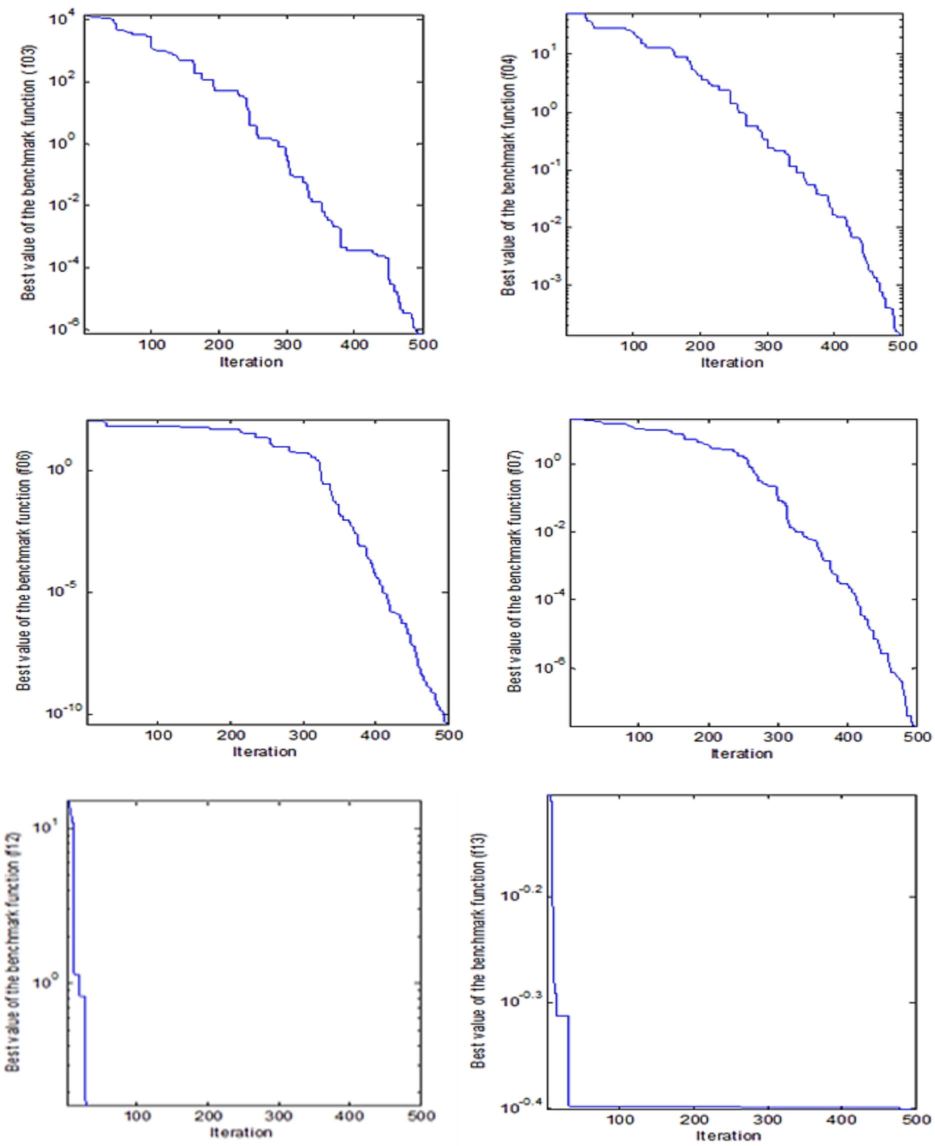


Figure 3. Convergence curves of the best solutions obtained for the selected benchmark functions based on MSCO algorithm

6.4. Simulation results and discussions

The nonlinear model of the gantry crane system is implemented in Simulink with trolley and sway PIDC controllers. The PIDC controller's parameters are tuned by SSCO and MSCO algorithms, and the obtained optimum values are shown in Tables 4 and 5, respectively. For MSCO algorithm, the objective function reaches the optimum value after (210) iterations as illustrated in Figure 4, the convergence curve for the system under PIDC controlling method. Figure 5 (a) shows the position response of the gantry crane model, which is tracking the reference input that was applied. It is noticed that from the simulation results, a small overshoot and rise time were obtained; hence, the modified algorithm provides a guarantee to control the system with best performance. As well as, Figure 5 (b) shows the oscillation response of the gantry crane model in rad, which is equal to zero after 5 seconds and the overshoot equal to 0.05 rad. Figure 6 shows the control signal of the gantry crane system that was controlled by the PIDC-MSCO method. The results reveal that, the control action and the payload swing decreased in a fast behavior to achieve a good response using the proposed controlling scheme.

Table 4. Optimized trolley and payload oscillation PIDC controllers' parameters based on SSCOA

PIDC Parameters	K_h	K_d	K_p	K_i	T_f
Optimized parameters for trolley controller	300	50	50	0.1	3
Optimized parameters for payload oscillation controller	100	1.03	1.72	1	7

Table 5. Optimized trolley and payload oscillation PIDC controllers' parameters based on MSCOA

PIDC Parameters	K_h	K_d	K_p	K_i	T_f
Optimized parameters for trolley controller	800	4.4	18.2	0	3.1
Optimized parameters for payload oscillation controller	1100	13.1	24.6	-0.3	10

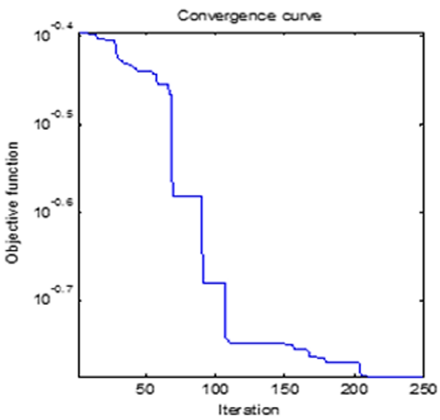
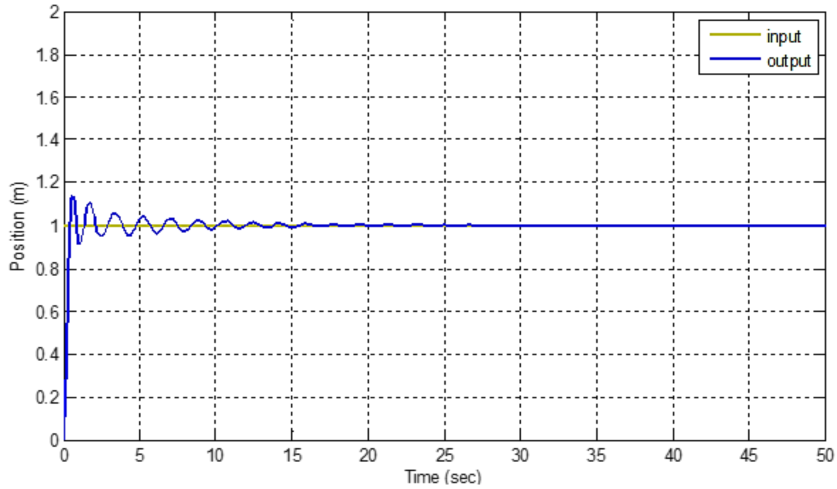
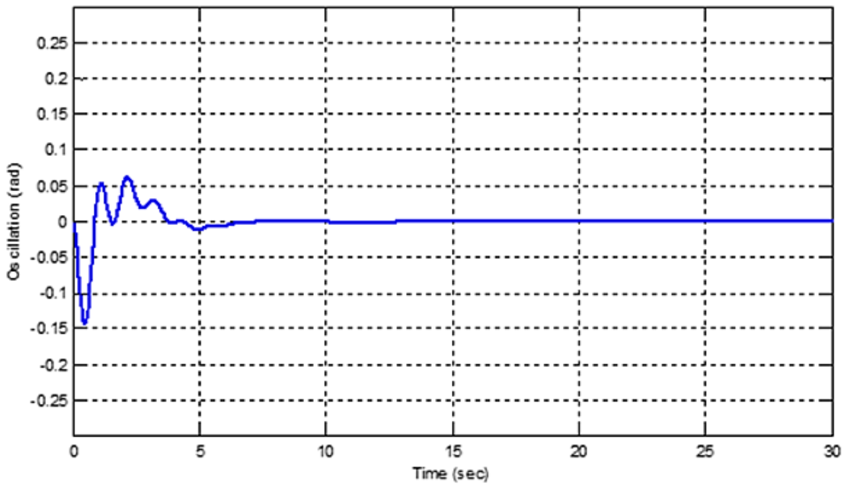


Figure 4. Convergence curve of the objective function of gantry crane system based on PIDC-MSCO controlling scheme

For SSCO algorithm, the objective function reaches to the best value (0.11) after (850) iterations. Figure 7 (a), shows the position response of the gantry crane system, which is tracking the unit step input. The overshoot and rise time that were attained by using PIDC-SSCO method are larger than the overshoot and rise time that were obtained based on PIDC-MSCO scheme. Therefore, the MSCO algorithm is suitable more than standard algorithm for finding the optimum PIDC parameters' values to control the system and with optimal performance. Figure 7 (b), shows the oscillation responses of the gantry crane model, which is equal to zero after 7 seconds and the overshoot equal to 1.1 rad. Finally, the developed MSCO algorithm showed good performance after examined based on a set of complex test problems and nonlinear gantry crane model. That is to say, the obtained results for the proposed optimization algorithm assured its performance for finding out the global optimal solutions. Additionally, MSCO algorithm have more competitive achievements as compared with the standard algorithm in terms of convergence rate, solution accuracy and escape from local optima indices.



(a)



(b)

Figure 5. System responses of the gantry crane system under PIDC-MSCO controlling scheme (a) trolley position (b) payload oscillation

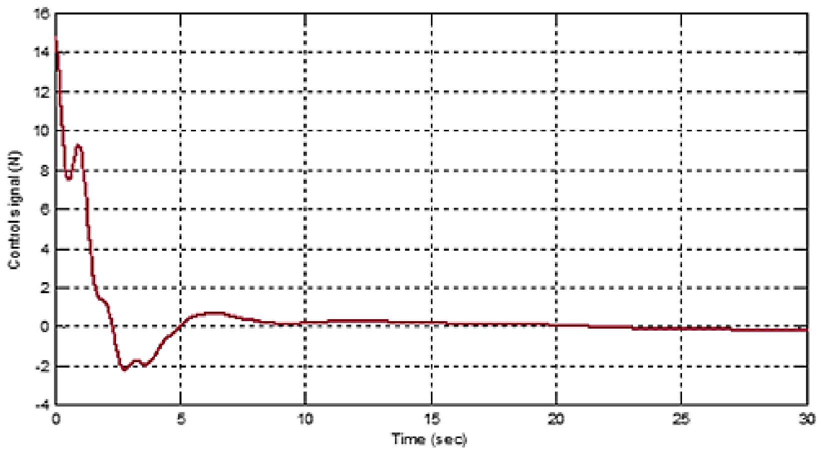
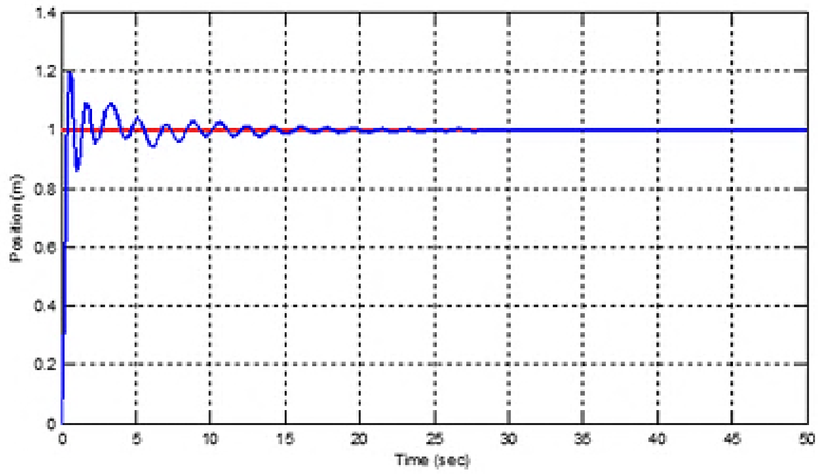
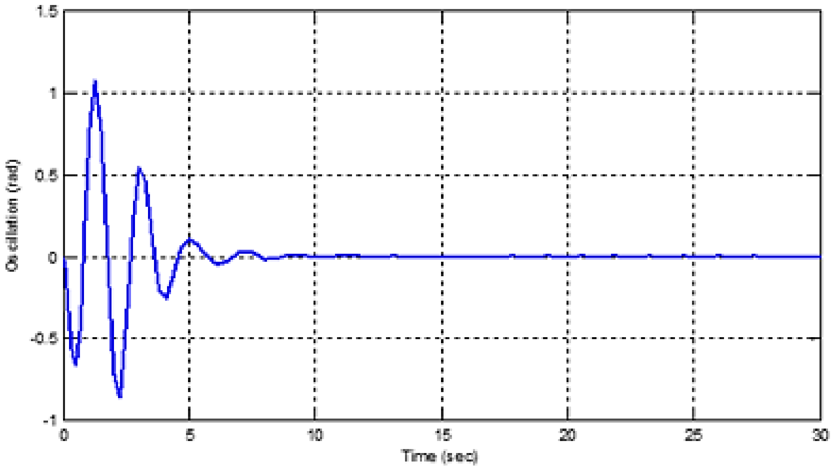


Figure 6. The control signal of the gantry crane system based on PIDC-MSCO controlling scheme



(a)



(b)

Figure 7. System responses of the gantry crane system under PIDC-SSCO controlling scheme; (a) trolley position (b) payload oscillation

7. CONCLUSIONS

The main contributions in this research work are proposing a new modified sine cosine optimization algorithm to solve highly complex optimization problems and introducing a modified PID controller tuned based on standard and modified SCO algorithms to strengthen the performance of the gantry crane system. The proposed MSCO algorithm is assessed under ten well-known benchmark problems as well as four composite test functions to unveil its power in terms of solution convergence speed, accuracy and computational time. The numerical results demonstrate that the unimodal functions clarify the exploitation ability of MSCO algorithm, the exploration feature of MSCO algorithm is guaranteed by the results of multimodal functions. Furthermore, the superior exploitation and exploration capabilities of the proposed algorithm are proved through applying the composite benchmark problems. The performance of optimized PIDC controller is validated with the simulation in MATLAB environment. The MSCO algorithm optimized PIDC controller with the recommended objective function is shown powerful in improving the step response of the trolley position as well as the payload oscillation as compared with SSCO-PIDC approach. Therefore, the optimized controller can efficiently move the gantry crane trolley in a reasonable time while minimizing the swing angle.

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