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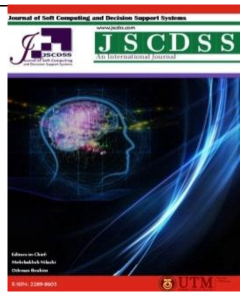

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PID Controller Optimization for Rotational Inverted Pendulum System Using Particle Swarm Optimization and Differential Evolution Algorithms

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Abstract

This paper presents stochastic search techniques, including Particle Swarm Optimization (PSO), Constriction Coefficient Particle Swarm Optimization (CPSO) and Differential Evolution (DE) algorithms for determining optimal Proportional-Integral-Derivative (PID) controller parameters attached to the Rotational Inverted Pendulum (RIP) system. This paper demonstrates in detail how to employ these proposed algorithms to optimize the performance index for balancing the pendulum in vertical-upright position. The efficiency of these intelligent strategies to tune PID gains is compared and evaluated based on the time response performance. The simulation results clearly demonstrate superior features of proposed tuning approaches, including easy implementation, and good computational efficiency. The overall results have validated that CPSO method yields better performance in control action compared to PSO and DE. The proposed approaches could generally be considered as an encouraging way for control of nonlinear industrial plants.

Keywords: Particle Swarm Optimization, Constriction Coefficient, Differential Evolution, Proportional-Integral-Derivative controller, Rotational Inverted Pendulum

1. Introduction

Rotary Inverted Pendulum (RIP) system as a well-known test platform system has always been one of the fundamental and controversial problems in control theory due to its inherent nonlinear and unstable dynamic behavior (Yan, 2003; Muskinja et al., 2006; Oltean, 2014). RIP has been also applied as a familiar system for various real life applications until today such as aerospace automobile control, robotics, control professionals, pendulum rides, rockets, robotic arm, the flight simulation of rocket or missile, and other transportation means (Jones, 1992; Drof et al., 1995; Lei et al., 1997; Van den berg, 2003; Muskinja et al., 2006).

During, the past years, numerous classical, as well as, modern control approaches such as Proportional Integral Derivative (PID) (Gaing, 2004), nonlinear control (Yan, 2003), Linear Quadratic Regulator (LQR) (Zhong et al., 2001), adaptive, and optimal (Sukontanakarn et al., 2006; Cong et al., 2009; Phuong et al., 2013) controllers have been introduced and applied on the balancing of RIP system. However, these control methodologies are theoretically challenging and complex to deal with the nonlinearities of RIP system. Therefore, designing a compatible and solvable controller which satisfies all of the design requirements of RIP system has become a vital issue.

Proportional-Integral-Derivative (PID) controller on the other hand, has been employed in various operating conditions of industrial plants and still in demand due to its simplicity in structure and robustness in performance (Visioli, 2001; Eibayomy et al., 2008). Nevertheless, the precisely tuning of the gains has become the drawback of this controller due to the higher order systems or plants, disturbances, and nonlinearities (Kwok et al., 1993; Gaing, 2004).

At the earlier times, Ziegler and Nichols (Ziegler et al., 1943) method has been broadly applied as classical tuning rule to adjust the PID controller parameters. However, the determination of optimal PID parameters by utilizing Ziegler-Nichols method still results in less optimal performance for a wide range of nonlinear plants (Visioli, 2001; Gaing, 2004).

To overcome these difficulties, the evolutionary algorithms have recently received great attention to provide a tuning capability of PID gains such as Simulated Annealing (SA) as a high efficient optimization method (Zhou et al., 1994) and Genetic Algorithm (GA) as a parallel search technique to tune PID parameters (Haupt et al., 1998; Rani et al., 2011; Hassanzadeh and Mobayen, 2011; Amanullah et al., 2014). Though, the SA method requires a large number of computations to find optimal solution (Subramanian et al., 2005), as well as, the natural process of GA would still result in slow convergence tendency (Haupt et al., 2004).

GA deficiencies such as similarity in structure of chromosomes (Kennedy et al., 1995; Gaing, 2004) is improved, using a novel global search strategy, called Particle Swarm Optimization (PSO) algorithm. PSO is a new meta-heuristic algorithm which is inspired by structure of a social system (Kennedy et al., 1995). It is widely applied within the control community due to its simple theory, easy implementation and less computational time which can lead to generate high-quality solutions with reasonable speed (Zadeh et al., 2008).

Moreover, the Differential Evolution (DE) algorithm has been successfully applied to various optimization fields because of its fast convergence and easy understanding (Nayak, 2011) in finding high efficient solutions . In this paper, the efficiency of different intelligent strategies are compared and evaluated for searching optimal PID controller as an optimization dilemma to make sure sufficient controlling behaviour of the closed-loop system of RIP.

Hence, in this study, we apply Lagrange concept in order to obtain mathematical model of RIP system. Moreover, we compare the efficiency of three intelligent algorithms including PSO, CPSO, DE methods which are used to determine optimal PID controller parameters.

2. Modelling Rotary Inverted Pendulum system

The rotational structure of the RIP system, as shown in Fig. 1, consists of a pendulum and a rotary arm rotating in vertical and horizontal plane, respectively where rotary arm mounted on the shaft of the servo motor is actuated by the servo motor, while the pendulum hangs downwards. The RIP system is inherently unstable, and should be dynamically remained in a steady state upright position, either by applying a torque at the actuating arm or by moving the actuating arm horizontally as part of a feedback system.

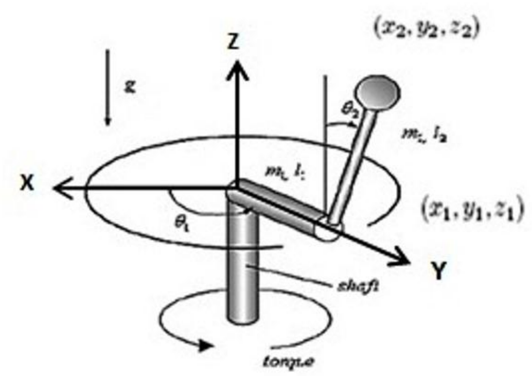

Fig. 1. The structure of a rotary inverted pendulum.

For this case, the physical parameters of RIP model PP-300 is assumed, shown in Table 1.

Table 1
Physical parameters of rotary inverted pendulum.

Parameter	Description	Value
M_1	Mass of Arm	0.056 kg
M_2	Mass of Pendulum	0.021 kg
L_1	Length of Arm	0.16 m
L_2	Length of Pendulum	0.16 m
R_a	DC motor armature resistance	0.2 Ω
K_r	Torque transmission coefficient	1.0 ($Nm.A^{-1}$)
K_b	Back-EMF coefficient	1.0 ($V.\sec$)
J_1	Inertia of Arm	0.00215058 $kg.m^2$
J_2	Inertia of Pendulum	0.00018773 $kg.m^2$
g	Gravity coefficient	9.81 $m.\sec^{-2}$
θ_1	Arm angle	
θ_2	Pendulum angle from vertical	

The dynamic equations of the RIP are developed on the Lagrange analysis. The Lagrange equation of motion is described as,

$$\frac{d}{dt}\left(\frac{\delta l}{\delta \dot{\theta}_i}\right)-\frac{\delta l}{\delta \theta_i}=Q_i \qquad i=1,...,n \tag{1}$$

where, Q_i denotes the external force.

In the Lagrange equation, the Lagrange function, L is defined based on the kinetic and potential energy of the system as follows:

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

where, T and U denote the kinetic and potential energy of the system, respectively.

In the first step, the kinetic and potential energy of the system should be described in terms of two coordinates (θ_1 and θ_2).

The velocities of two links can be derived from their position. The position of each of two links in terms of x, y, and z components is expressed as,

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}=\begin{bmatrix} l_1\cos\theta_1 \\ l_1\sin\theta_1 \\ 0 \end{bmatrix}, \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix}=\begin{bmatrix} l_1\cos\theta_1 - l_2\sin\theta_1\sin\theta_2 \\ l_1\sin\theta_1 + l_2\cos\theta_1\sin\theta_2 \\ -l_2\cos\theta_2 \end{bmatrix} \tag{3}$$

The total kinetic energy of the system is the sum of kinetic energy of the rotary arm m_1, and the pendulum m_2, are differentiated with respect to time.

$$\begin{aligned} T &= 1/2J_1\dot{\theta}_1^{\,2} + 1/2m_1(\dot{x}_1^{\,2}+\dot{y}_1^{\,2}+\dot{z}_1^{\,2}) \\ &\quad + 1/2J_2\dot{\theta}_2^{\,2} + 1/2m_2(\dot{x}_2^{\,2}+\dot{y}_2^{\,2}+\dot{z}_2^{\,2}) \end{aligned} \tag{4}$$

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Then, the kinetic energy of two links based on their velocities is developed to gain the total kinetic energy of the system.

$$T = 1/2J_1\dot{\theta}_1^2 + 1/2m_1 l_1^2\dot{\theta}_1^2 + 1/2J_2\dot{\theta}_2^2 + 1/2m_2((l_1^2 + l_2^2 sin^2\theta_2)\dot{\theta}_1^2 + l_2^2\dot{\theta}_2^2 + 2l_1 l_2\dot{\theta}_1\dot{\theta}_2 cos\theta_2) \tag{5}$$

The potential energy of the system is stored in the pendulum in the form of gravitation. The potential energy of the system, U can be defined as,

$$U = m_2 g l_2 cos\theta_2 \tag{6}$$

Therefore, the Lagrange equation of system is yielded by substituting Eqs. (5) and (6) into Eq. (2).

$$L = 1/2J_1\dot{\theta}_1^2 + 1/2J_2\dot{\theta}_2^2 + 1/2(m_1 + m_2)l_1\dot{\theta}_1^2 + 1/2m_2 l_2^2 sin^2\theta_2\dot{\theta}_1^2 + 1/2m_2 l_2^2\dot{\theta}_2^2 + m_2 l_1 l_2\dot{\theta}_1\dot{\theta}_2 cos\theta_2 - m_2 g l_2 cos\theta_2 \tag{7}$$

The derivatives of Lagrange function can then be represented in Eqs. 8 and 9 by substituting the derivatives of $\theta_1(t)$ and $\theta_2(t)$ from Eq. (7).

$$\frac{d}{dt}\left(\frac{\partial l}{\partial\dot{\theta}_1}\right) - \frac{\partial l}{\partial\theta_1} = \tau \tag{8}$$

$$\frac{d}{dt}\left(\frac{\partial l}{\partial\dot{\theta}_2}\right) - \frac{\partial l}{\partial\theta_2} = 0 \tag{9}$$

Where, the relation between the control torque (τ) and the control voltage *(e)* is given by Eq. (10) (Uo-Huang, 2006),

$$\tau = \frac{K_b}{R_m}e - \frac{K_b^2}{R_m}\dot{\theta}_1 \tag{10}$$

The nonlinear equations of motion without considering friction effects can be represented in Eqs. (11) and (12) (Bejarbaneh, 2012).

$$J_1\ddot{\theta}_1 + (m_1 + m_2)l_1^2\ddot{\theta}_1 + m_2 l_1 l_2\ddot{\theta}_2 cos\theta_2 + m_2 l_2^2 sin^2\theta_2\ddot{\theta}_1 + 2l_2^2 m_2\dot{\theta}_2\dot{\theta}_1 cos\theta_2 sin\theta_2 - m_2 l_1 l_2\dot{\theta}_2^2 sin\theta_2 = \tau \tag{11}$$

$$J_2\ddot{\theta}_2 + m_2 l_2^2\ddot{\theta}_2 + m_2 l_1 l_2\ddot{\theta}_1 cos\theta_2 + m_2 g l_2 sin\theta_2 - m_2 l_2^2\dot{\theta}_1 sin\theta_2 cos\theta_2 = 0 \tag{12}$$

Eqs. (11) and (12) can be presented in the matric form as below,

$$\begin{bmatrix} J_1 + (m_1 + m_2)l_1^2 + m_2 l_2^2\sin^2\theta_2 & m_2 l_1 l_2\cos\theta_2 \\ m_2 l_1 l_2\cos\theta_2 & J_2 + m_2 l_2^2 \end{bmatrix}\begin{bmatrix}\ddot{\theta}_1 \\ \ddot{\theta}_2\end{bmatrix} + \begin{bmatrix} l_2^2 m_2\dot{\theta}_2\cos\theta_2\sin\theta_2 & l_2^2 m_2\dot{\theta}_1\cos\theta_2\sin\theta_2 - m_2 l_1 l_2\dot{\theta}_2\sin\theta_2 \\ -m_2 l_2^2\dot{\theta}_1\sin\theta_2\cos\theta_2 & 0 \end{bmatrix}\begin{bmatrix}\dot{\theta}_1 \\ \dot{\theta}_2\end{bmatrix} + \begin{bmatrix} 0 \\ m_2 g l_2 sin\theta_2 \end{bmatrix} = \begin{bmatrix}\tau \\ 0\end{bmatrix} \tag{13}$$

The linear model of RIP around configuration point ($\theta_2 = \pi$) is given by Eq. (14).

$$\begin{bmatrix} J_1 + (m_1 + m_2)l_1^2 & -m_2 l_1 l_2 \\ -m_2 l_1 l_2 & J_2 + m_2 l_2^2 \end{bmatrix}\begin{bmatrix}\ddot{\theta}_1 \\ \ddot{\theta}_2\end{bmatrix} + \begin{bmatrix} 0 \\ -m_2 g l_2\theta_2 \end{bmatrix} = \begin{bmatrix} \frac{K_b}{R_m}e - \left(\frac{K_b^2}{R_m}\right)\dot{\theta}_1 \\ 0 \end{bmatrix} \tag{14}$$

$$\ddot{\theta}_1 = \left[\frac{-(J_2 + m_2 l_2^2)\left(\frac{K_b^2}{R_m}\right)}{\Delta}\right]\dot{\theta}_1 - \left[\frac{m_2^2 l_2^2 l_1 g}{\Delta}\right]\theta_2 + \left[\frac{(J_2 + m_2 l_2^2)(\frac{K_b}{R_m})}{\Delta}\right]e \tag{15}$$

$$\ddot{\theta}_2 = \left[\frac{J_1 g l_2 m_2 + g l_2 m_2 l_1^2(m_1 + m_2)}{\Delta}\right]\theta_2 + \left[\frac{-(-m_2 l_1 l_2)(-\frac{K_b^2}{R_m})}{\Delta}\right]\dot{\theta}_1 + \left[\frac{-m_2 l_1 l_2(\frac{K_b}{R_m})}{\Delta}\right]e \tag{16}$$

where,

$$\Delta = J_1(J_2 + m_2 l_2^2) + J_2 l_1^2(m_1 + m_2) + l_1^2 m_2 m_1 l_2^2$$

The linear model of a RIP system consists of mathematical equations as determined by Eqs. (15) and (16) is shown in Fig. 2.

With regard to the numerical value of RIP parameters in Table1, the state space form of linearized RIP model is given by Eq. (17).

$$\begin{bmatrix}\dot{\theta}_1 \\ \dot{\theta}_2 \\ \ddot{\theta}_1 \\ \ddot{\theta}_2\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -0.033339 & -3.788841 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0.02857712 & 55.80171556 & 0 \end{bmatrix}\begin{bmatrix}\theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2\end{bmatrix} + \begin{bmatrix} 0 \\ 1.829 \\ 0 \\ -1.563 \end{bmatrix}e \tag{17}$$

3. Controller design

3.2 PID controller design

For this research, the controller design will focus on the simple PID controller algorithm. The main reason to choose the PID controller is because it much easier to design compared to other controllers. With this under-actuated system, it is necessary to apply two PID controllers: one for controlling θ_1 (PID 1) and the other one for controlling θ_2 (PID 2). The initial angular position of arm, θ_1, and the pendulum, θ_2, is assumed zero and 0.087 radian, respectively. The primary goal is to turn the arm and the pendulum to zero radian with the gains provided by PSO, CPSO and DE. The nonlinear model of RIP is applied to validate and confirm the PID control

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ability tuned by evolutionary algorithms. The nonlinear equations for modeling RIP system are given by Eqs. (11) and (12).

The strategy of the rotary inverted pendulum control system is represented in Fig. 3.

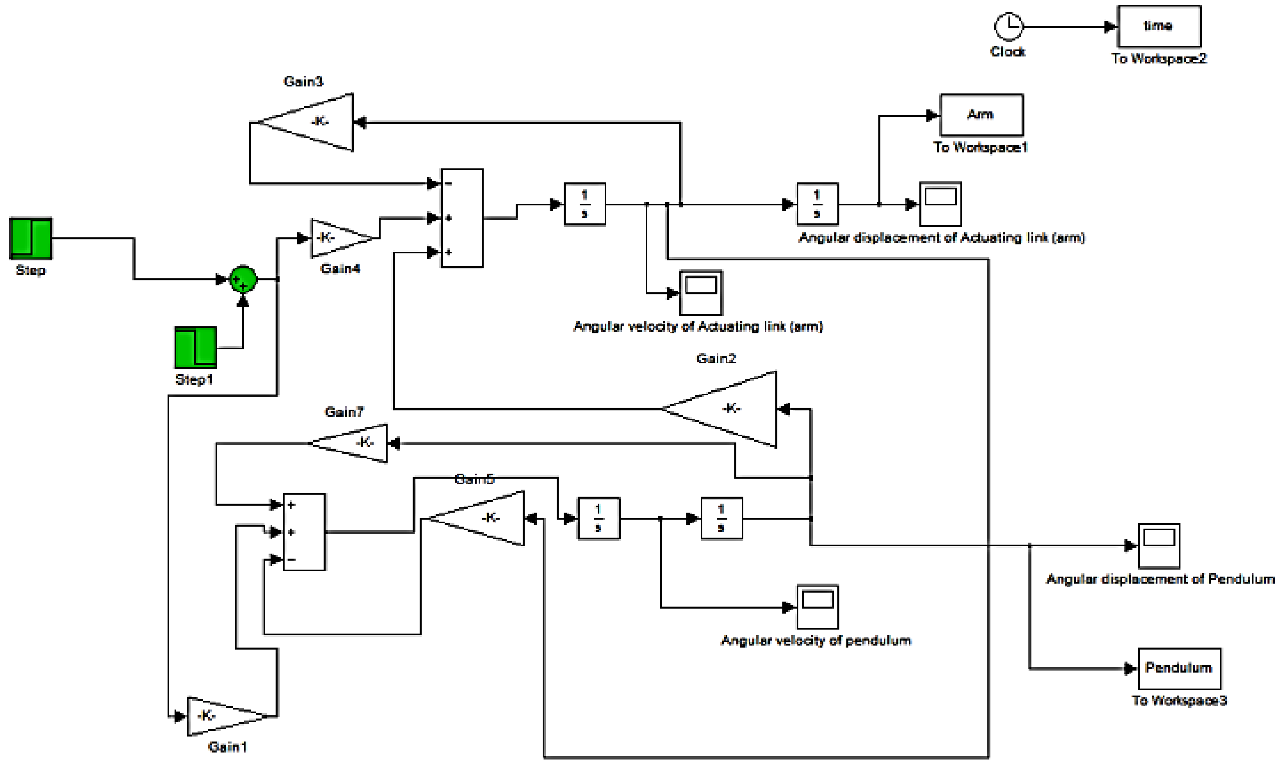

Fig. 2. Simulink model of linear RIP system.

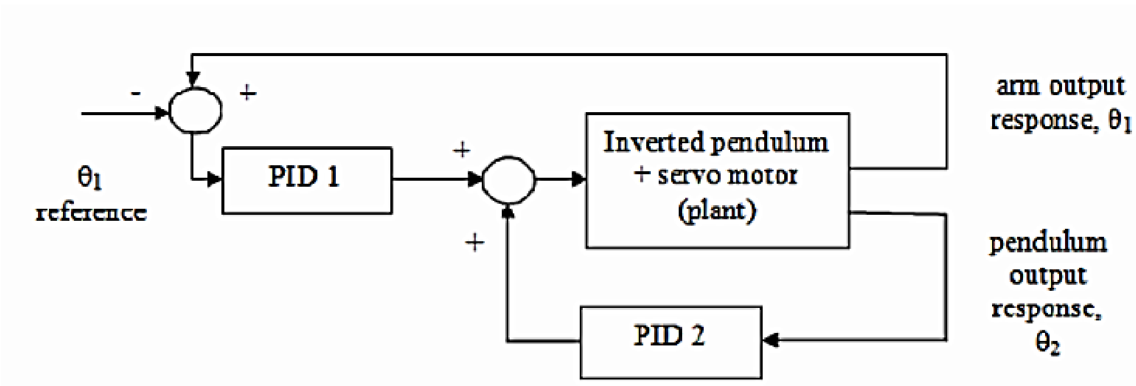

Fig. 3. The structure of the rotary inverted pendulum control system.

The Simulink block diagram of the RIP on MATLAB platform is shown in Fig. 4, where the angular displacement of arm θ_1, is configured by the input voltage V, the main objective is to stabilize the pendulum angle, θ_2 as zero so that the inverted pendulum maintains its stability (Akhtaruzzaman et al., 2010; Rani et al., 2012).

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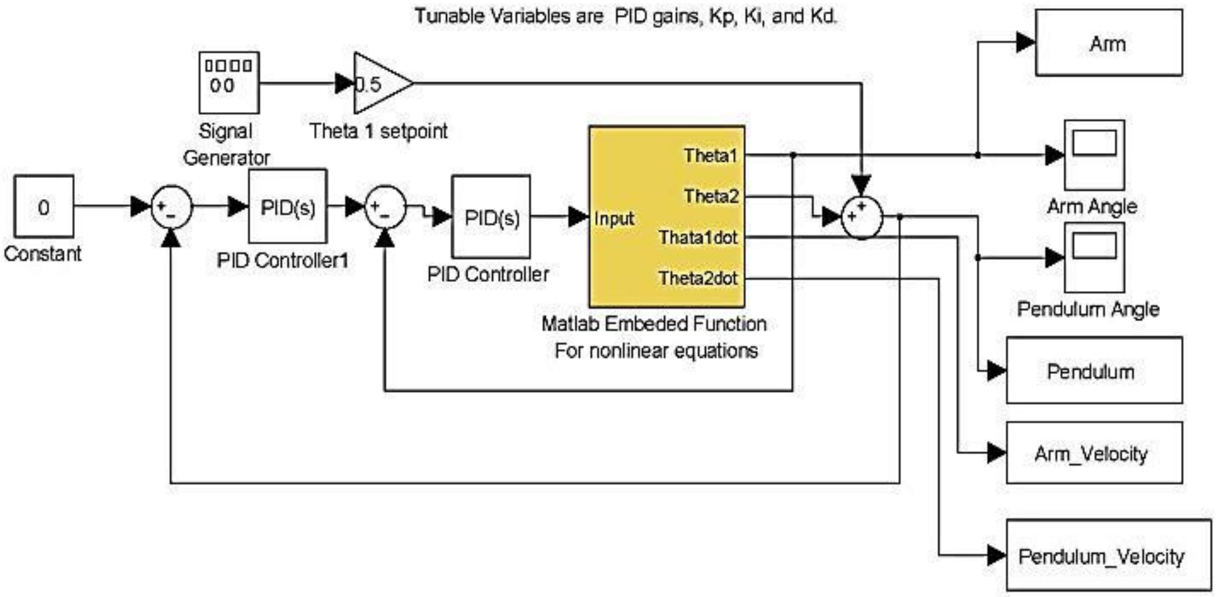

Fig. 4. Simulink block diagram of the proposed PID strategy.

4. Particle Swarm Optimization

4.2 Overview of original PSO

Particle swarm optimization algorithm was introduced first time by Eberhart and Kennedy in 1995 (Kennedy et al., 1995). It is a new meta-heuristic search method that uses the social behaviour of swarm of birds as a source of inspiration. In this paper, this algorithm serves PID controller on RIP plant associated with nonlinearities. First of all, PSO algorithm creates a population of random particles.

These particles have two critical abilities: their memory of their own best position (P_{best}) and their awareness of the swarm best position (G_{best}). Next, Particles of a swarm share good positions between each other and update their own position and velocity according to Eqs. (19) and (20). In this problem, search space is three-dimensional axes that are K_p, K_i, and K_d axes. The algorithm procedure can be expressed in following flowchart.

$$\mathrm{X}_i=(X_{iP},X_{iI},X_{iD})=(K_p,K_i,K_d)$$
$$V_i=(\mathrm{V}_{iP},\mathrm{V}_{iI},\mathrm{V}_{iD}) \qquad (18)$$

$$\mathrm{v}(\mathrm{k}+1)_{\mathrm{i,j}}=\mathrm{w.v}(\mathrm{k})_{\mathrm{i,j}}+\mathrm{c}_1\mathrm{r}_1(\mathrm{gbest}-\mathrm{x}(\mathrm{k})_{\mathrm{i,j}})$$
$$+\mathrm{c}_2\mathrm{r}_2(\mathrm{pbest}_j-\mathrm{x}(\mathrm{k})_{\mathrm{i,j}}) \qquad (19)$$

$$\mathrm{x}(\mathrm{k}+1)_{\mathrm{i,j}}=\mathrm{x}(\mathrm{k})_{\mathrm{i,j}}+\mathrm{v}(\mathrm{k})_{\mathrm{i,j}} \qquad (20)$$

Where, $V(\mathrm{k})_{\mathrm{i},j}$ and $\mathrm{x}(\mathrm{k})_{\mathrm{i,j}}$ are the velocity and position of particle i and dimension j, respectively, whereas, C_1,C_2 are the acceleration factors, r_1,r_2 are random numbers, w is the inertia weight factor, p_{best} and g_{best} are the best position of a particle and swarm, respectively.

For all algorithms, in every problem, a fitness function must be defined. In this problem, the aim is to minimize every performance index of F function, including of Integral Time Absolute Error and the overshoot criteria. This cost function is applied to evaluate its ability to tune PID controller attached to RIP system.

$$F=\alpha*\mathrm{ITAE}+\beta*\mathrm{Overshoot} \qquad (21)$$

Where, ITAE is the Integral Time Absolute Error criteria, α and β are improvement factors, respectively.

According to the flowchart of original PSO indicated in Fig. 5. First, the lower and upper bound of the controller parameters are specified and then the RIP and PSO parameters, including, number of iteration, population size, and initial random of particle position are defined. The program calls the RIP model from Simulink part in MATLAB platform and accumulates it (α.ITAE+β.Over-Shoot) as fitness value. Secondly, the personal and global best particle position are stored and updated via velocity update formula indicated in Eq. 18. The simulation will only stop when the iteration exceeds maximum defined number of iteration. Eventually, the minimum value of each iteration will give the best value of PID parameters.

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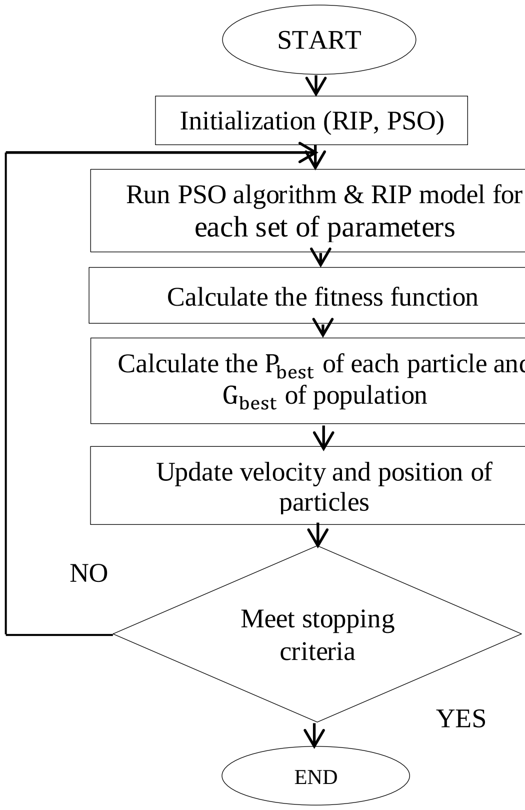

Fig. 5. The flowchart of PSO-PID controller design.

4.3 Constriction Coefficient. PSO

In order to more exploration of complex search area in 2002, constriction coefficient approach was proposed by Clerc and Kennedy (Clerc et al., 2002) which is used in this paper. This method is introduced a specific parameter 'χ' as constriction factor. The velocity update formula of adaptive model excluded the inertia weight ω and the maximum velocity (V_{max}) parameter. The velocity update formula can be expressed as follow,

$$V_{id}(t+1) = \chi\ [V_{id}(t) + C_1.\varphi_1.(P_{id}(t) - X_{id}(t)) + C_2.\ \varphi_2.(g_{id}(t) - X_{id}(t))] \quad (22)$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \quad (23)$$

where,

$$\chi = \frac{2}{\left|4 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}\ with\ \varphi = C_1 + C_2 \quad (24)$$

In order to initialize the parameters of PSO algorithm, constriction coefficient approach is proposed a specific range for Inertia weight factor (w) and acceleration factors (C_1, C_2) of PSO algorithm as,

$$\varnothing_1, \varnothing_2 > 0 \ \text{ where } \varnothing \triangleq \varnothing_1 + \varnothing_2 > 4 \quad (25)$$

$$\chi = \frac{2}{\left|4 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|} \quad (26)$$

Where, χ denotes constriction coefficient factor.

$$w = \chi\ ,\ C_1 = \chi.\phi\ and\ C_2 = \chi.\phi_2 \quad (27)$$

The constriction coefficient method balances the requirement of searching for local and global search which leads to the fast convergence of the particles through all period of time. As during the search, the local search is applied when the local best position and the global best position are close to each other, whereas when the local best position and the global best position are far away from each other the global search is performed (Das et al., 2008).

5. Deferential Evolution Algorithm

Differential evolution algorithm was introduced first time by Price and Storn in 1997 (Storn et al., 1997). It is a population based algorithm.

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The DE algorithm is a population based algorithm like genetic algorithm which applies the three operators; crossover, mutation and selection. The main dissimilarity DE with GA is in finding better solutions as genetic algorithm depends on crossover whereas DE relies on mutation operation. Also, DE utilizes a modern crossover operator that can obtain more information to search for a better solution in comparison with GA. In this paper, DE algorithm serves PID controller on nonlinear RIP plant as a task involving of three parameters represented by a 3-dimensional vector. This algorithm starts with a population of random solution vectors and then this population is continually updated by applying three operators, including mutation, crossover and selection operators as this procedure is shown in Fig. 6.

In mutation section three independent parameter vectors (r_1, r_2, and r_3 vectors) are selected randomly from the population. Next, a scalar factor (F) measures the difference of two vectors and the scaled difference are added to the third one where trial vector $V_i(t)$ is generated as follows,

$$V_{i,j}(t+1) = X_{r1,j}(t) + F.\left(X_{r2,j}(t) - X_{r3,j}(t)\right) \quad (28)$$

In the crossover section the target vector is combined with the trial vector.

$$u_{ji,G+1} = \begin{cases} V_{ji,G+1} & if\ (randj \le CR)\, or\ j = rni \\ q_{ji,G} & if\ (randj > CR)\, and\ j \ne rni \end{cases} \quad (29)$$

Finally, in selection section the new generated solution by the mutation and crossover operations is evaluated to choose the better one (Nayak, 2011).

$$X_{i,G+1} = \begin{cases} u_{i,G+1} & if\ \left((u_{i,G+1}) < f(X_{i,G})\right) \\ x_{i,G} & \text{otherwise} \end{cases} \quad (30)$$

6. RIP control system design by using intelligent techniques

The Simulink model of RIP control system by using stochastic search methods and tuning parameters of PSO and DE are presented in Fig. 7 and Table 2, respectively.

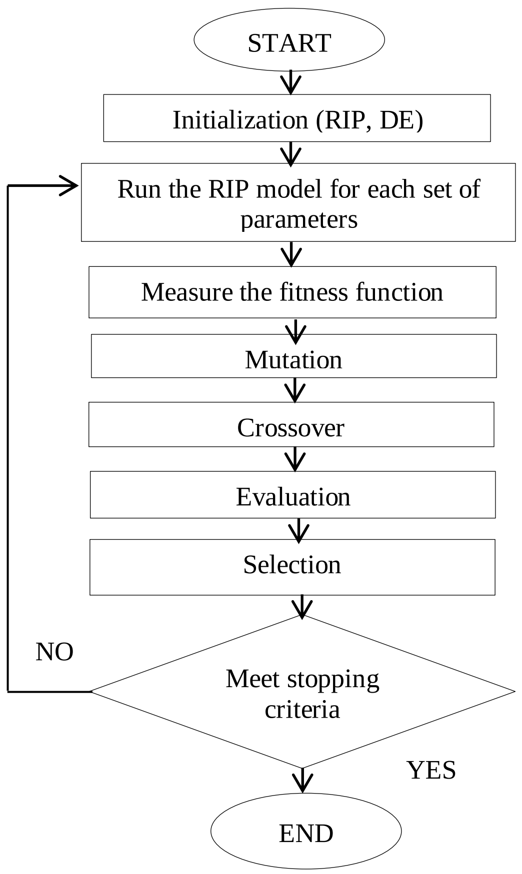

Fig. 6. The flowchart of DE-PID controller design.

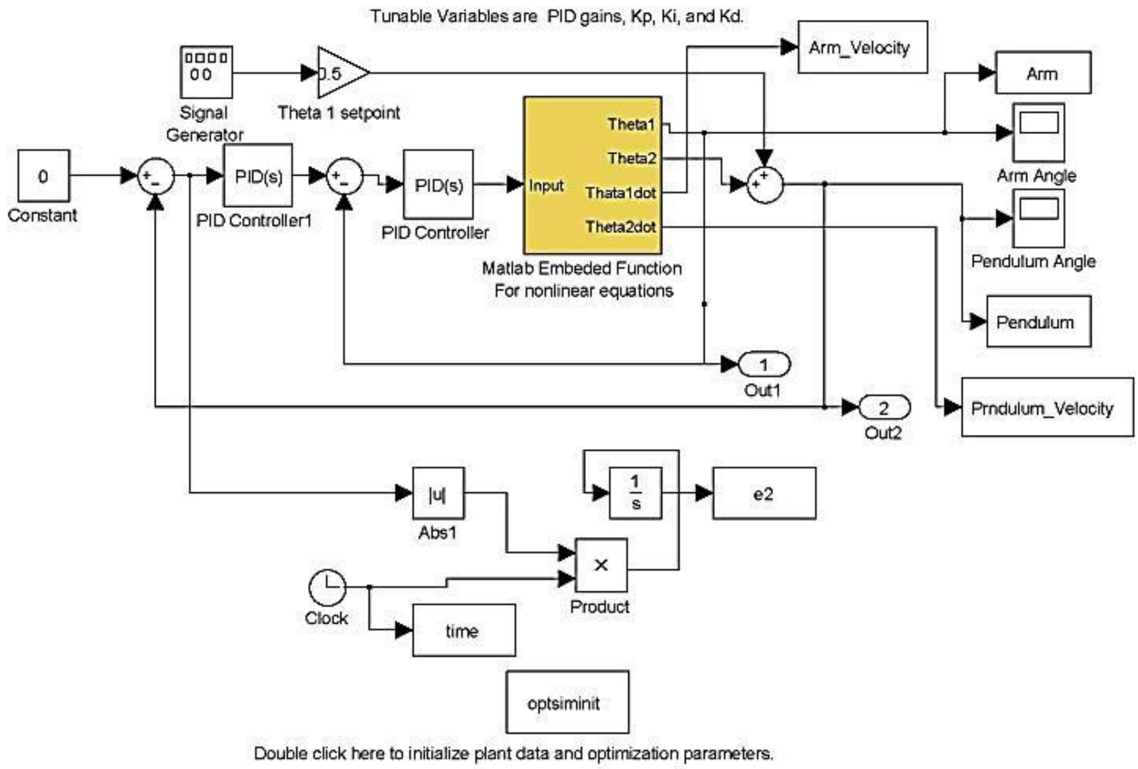

Fig. 7. Simulink design of PID controller adjustment by using stochastic algorithms.

Table 2
Tuning parameters.

Parameter	Value
Lower bound $[K_p\ K_i\ K_d]$	[0 0 0]
Upper bound $[K_p\ K_i\ K_d]$	[50 50 50]
Stopping criteria (iteration)	50 and 100
Population size	50
Crossover probability	0.2
Scaling factor	Between 0.2 and 0.8

7. Simulation results

7.2 Convergence curve

The Simulation tool is applied to investigate the dynamic behavior and compare PID controller's convergence characteristics. The number of function evaluation during the computation processes is considered. This value displays the accuracy of algorithms. As the convergence tendency of pendulum response by utilizing PSO, CPSO and DE methods is depicted in Figs. 8, 9, and 10 respectively.

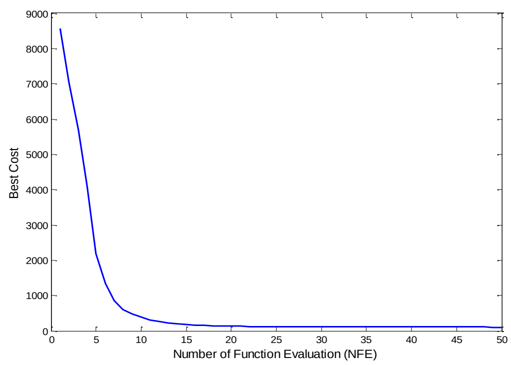

Fig. 8. Convergence tendency of PSO-PID controller.

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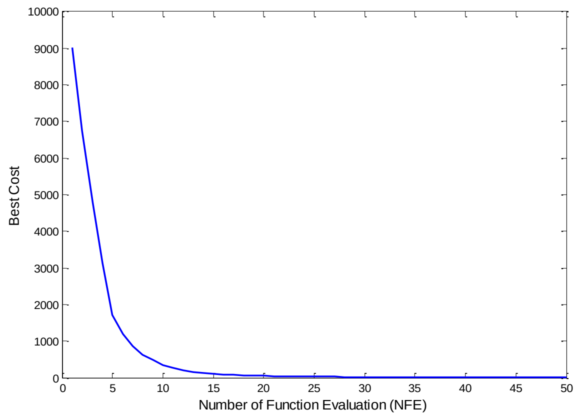

Fig. 9. Convergence tendency of CPSO-PID controller.

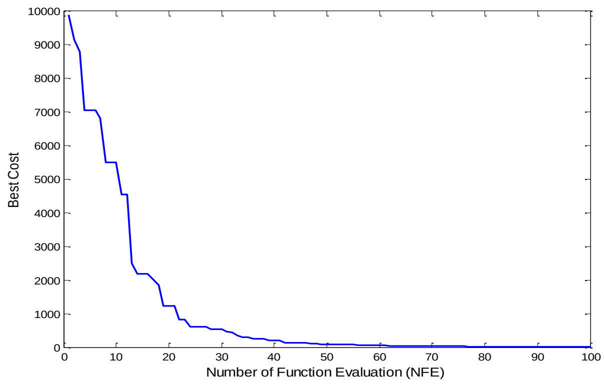

Fig. 10. Convergence tendency of DE-PID controller.

7.3 Performance based on servo behaviour

The performance of tuning techniques of PID parameters is evaluated with regard to minimum overshoot, less rise time and etc. Also, the reference signal tracking behavior is evaluated on the RIP system. For analysis of this performance, the typical positions output response of PSO-PID, CPSO-PID, and DE-PID controllers are indicated in Figs. 11, 12, and 13, respectively.

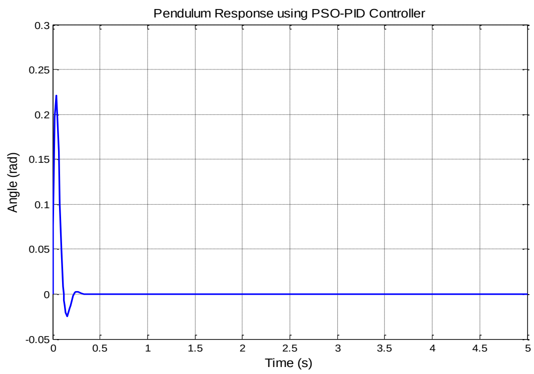

Fig. 11. The pendulum response using PSO-PID controller.

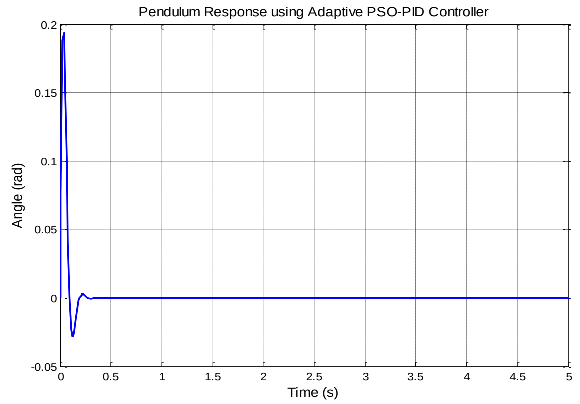

Fig. 12. The pendulum response using CPSO-PID controller.

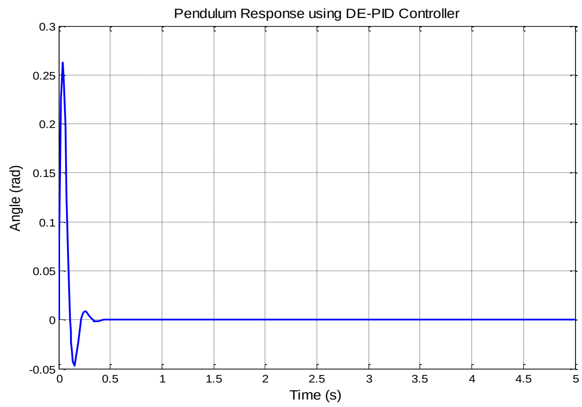

Fig. 13. The pendulum response using DE-PID controller.

7.4 Comparison between different methods based on servo behaviour

A comparison of time-response performance by using intelligent techniques to control the pendulum angle and arm position is shown in Figs. 14 and 5 respectively.

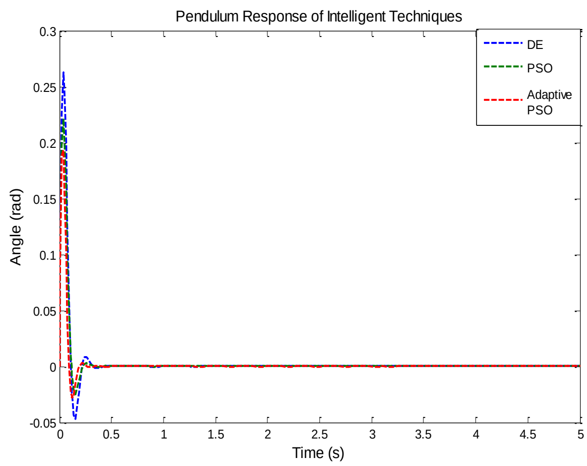

Fig. 14. Comparative results of intelligent techniques.

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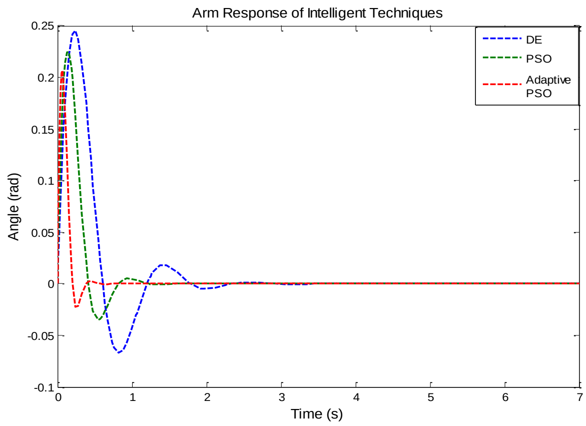

Fig. 15. Comparative results of intelligent techniques.

The simulation result of the best solution to stabilize the pendulum angle in terms of number of iteration are summarized in Table 3, the time response performance of system is improved utilizing CPSO in comparison with DE and PSO techniques.

Furthermore, the convergence tendency of CPSO and PSO algorithms are faster than DE algorithm because of less number of iteration to obtain the minimum value of cost function. In addition, with regarding to overall cost values, CPSO has less cost value compared to PSO and DE techniques, showing that this method achieves better accuracy and smooth time response in control action. Though, all of algorithms establish efficient convergence of best cost value using the same cost function and simulation conditions.

Table 3
Best values of PID performance by using DE, PSO, and C PSO .

Parameter	DE	PSO	CPSO
K_p	48.01	43.8	42.41
K_i	0.0038	0.0011	0.011
K_d	12.34	12.10	13.33
T_r (s)	0.0025	0.0019	0.0017
T_s (s)	0.2886	0.2112	0.1938
E_{ss}	0.00	0.00	0.00
Peak Time (s)	0.2631	0.2214	0.1938
Cost	19.17	17.13	9.48
Iteration	100	50	50

8. Conclusion

In this paper, three optimization approaches proposed including, PSO, constriction coefficient. PSO and DE algorithms for tuning of PID controller attached to the nonlinear model of Rotary Inverted Pendulum system. Each of the algorithms was evaluated in different number of iteration as PSO and CPSO methods with 50 runs and DE method with 100 runs and these techniques gave different values at each program run due to the structure of algorithms based on the generation of random values. From the test problem analysis, the CPSO method is observed to have the best quality of solution compared to other two techniques. Whereas, with regard to the PID performance, DE algorithm requires more generation to fast convergence in comparison with other algorithms.

Hence, CPSO can be considered more efficient approach in terms of better accuracy, less iteration and computational time compared to the traditional PSO and DE algorithms. Through the simulation results, it is obvious that these proposed intelligent techniques establish a new prospective to find efficient optimal solution of PID gains for any nonlinear industrial plants with unknown process parameters. The implementation of hybrid stochastic algorithms such as PSO-DE and GA-PSO for designing adaptive controllers will be another challenging task in the future.

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