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Synergetic Control-Based Sea Lion Optimization Approach for Position Tracking Control of Ball and Beam System

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ABSTRACT

One of the most difficult systems to control is the ball and beam (BnB) system due to its under-actuation, instability, and nonlinearity. To address these challenges, this paper presents an application of using the nonlinear synergetic control (SC) algorithm for position tracking control of the BnB system. A swarm optimization method based on sea lion optimization (SLO) has also been used to achieve an optimum dynamic performance by adjusting the suggested controller's parameter. The Integral Time of Absolute Errors (ITAE) is employed by the SLO as an objective function to adjust the design parameters of the suggested SC. Using MATLAB software, a comparison has been made between the SC controller and the classical state feedback controller (SFC) to test the effectiveness of the suggested control algorithm. The findings illustrate that the suggested SC offers better transient response in terms of reducing the settling time and the overshoot than SFC. The effect of the external disturbance has also been examined. It has been found that SC provides more robustness performance than SFC.

1. Introduction

The Ball and Beam (BnB) system is an electro-mechanical system can be used to evaluate a wide range of control strategies. Therefore, BnB is a popular educational experiment in control labs [1]. Basically, it is a steel ball rolling on a long beam, with the ball frequently balanced at a specific point by adjusting the beam's angle [2]. Regardless the simplicity of the system, BnB is highly nonlinear, under-actuated and unstable system [3]. The under-actuated systems are defined as systems have fewer actuators than the degrees of freedom to be controlled. Some of these systems cannot be directly controlled, and then its required highly complicates the design of control algorithms. Numerous studies including linear and nonlinear control strategies have been conducted to accomplish the intended control goals namely, regulation and stabilization of the system. A standard proportional-derivative (PD) controller was introduced by Yu and Ortiz in [4] to regulate the BnB system. In [5], Maalini et al. proposed the proportional-integral-derivative (PID) controller to control the BnB system. To enhance the performance of the PID controller, Ali et al. tuned the PID controller's design gains for a linearized version of the BnB system using particle swarm optimization (PSO) [6]. The H2 and the linear quadratic regulator (LQR) controllers are both optimal controller that has been applied by Hung et al. [7]. The results of this study have showed that both controllers are able to track the reference inputs effectively. However, the H2 controller exhibited a faster response than the LQR controller. Another controller has been suggested by Amjad et al. for ball's position in a BnB system. Fuzzy Logic Controller (FLC) was proposed and compared to PID controller [2], [8]. Based on the result data, the efficiency of FLC has better performance than PID controller.

Hamid and Elaheh in [9] have developed a type-2 fuzzy state feedback controller. The results demonstrated that BnB system was able to be stabile by this controller. To control the ball location, Ezzabi et al. in [3] have suggested a nonlinear backstepping control (BSC). The goal was to design a controller to reduce the amount of energy and overshoot while controlling the ball location. Can and Başçi in [10], has proposed sliding mode controller (SMC). SMC applied in both outer loop and inner loop. The outer loop applied to control the ball position after changing the beams' angle. While the inner loop is used to change the beam's location by producing an appropriate servo motor position angle through calculation the voltage required. A comparison for the responses has been made with PI controller, and it has showed SMC accuracy, reference tracking, and quick change reaction is better than PI controller. For robust tracking control of BnB systems, Khan et al. provided a comparison between classical SMC and integral SMC (ISMC) [11]. The simulation findings prove that the ISMC method has a better response despite external disturbance and parameter uncertainty. A pair of decoupled fuzzy sliding-mode controllers (DFSMCs) has been developed by Chang et al. in [12]. Moreover, the ant colony optimization (ACO) is used to optimize the controller parameters for the purpose of improving the mentioned control algorithm.

From what was mentioned before, the BnB system's dynamic performance has been improved using different control algorithms. Moreover, there are some robust controllers, such as synergistic controller (SC), which is a reliable nonlinear control that can handle model nonlinearities, external disturbances, and uncertainties, have not been implemented for the mentioned system. SC algorithm has been used in the control of various engineering fields such as aerospace, energy, and other systems [13]-[15]. Therefore, to control the ball's position on the beam, SC method will be used. The generated control signal of the SC method represents the variable that needs to be modified to control the response of the nonlinear system according to the desired performance. Swam optimization approaches are used to find the best controller parameters since they are more effective than the trial-and-error method [16]-[21]. Because of the effectiveness of swarm methods, numerous optimization issues have been solved using swarm optimization [22]-[27]. Thus, the sea lion optimization (SLO) method is used to find the best SC parameters. To evaluate the performance of the proposed SC method, a comparison between the proposed SC and the state feedback controller (SFC) has been done. The rest of the paper is organized as follows: The mathematical model of the BnB system is presented in Section 2. The design of the SC method is covered in Section 3. Section 4 is specified for sea lion optimization. In Section 5, the simulation results are discussed, while the conclusion is provided in Section 6.

2. Mathematical Model

The BnB system mathematical model will be discussed in this section. A one-degree ball is traveling along a beam according to a specific angle as shown in Fig. 1. x represents the ball's position while l is the beam's length. In terms of the lever arm, a servo gear is used to control the beam. During the rotation of the servo gear at an angle θ, the beam moves from being horizontal to an angle ∅. As a result of gravity, the ball rolls along the beam [11]. The voltage represents the system's input while the angular position of the leverage arm and linear position of the ball on the beam are the outputs. The motion of the ball can be described by:

$$m\ddot{x} = f_2 - f_1 \tag{1}$$

where m is the mass of the ball, $\ddot{x}$ is the acceleration of the ball, the forces exerted on the ball by gravity and inertia are denoted by the f_1 and f_2, respectively. Considering the force on the ball due to its inertia is given by:

$$f_1 = \frac{T_b}{r} \tag{2}$$

where the radius of the ball r and T_b is the torque which is computed as follows:

$$T_b = \frac{I_b}{r}\ddot{x} \tag{3}$$

where I_b is the inertia of the ball. Substitutes Eq. (3) into Eq. (2) gives:

$$f_1 = \frac{I_b}{r^2}\ddot{x} \tag{4}$$

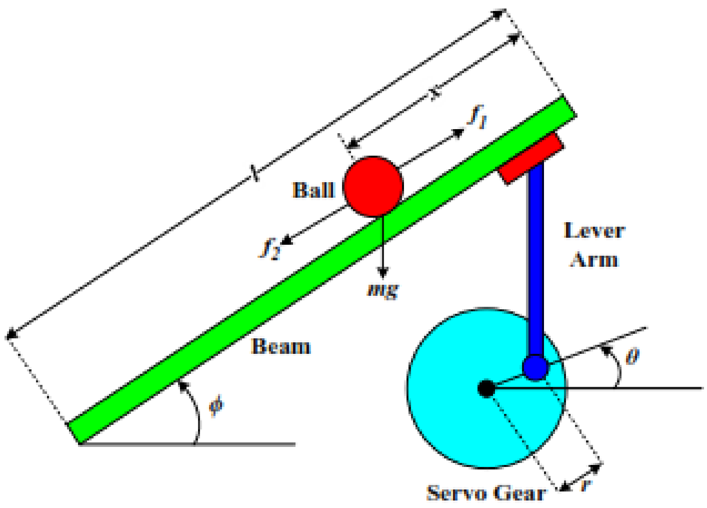

Fig. 1. Schematic diagram of ball and beam system

When the beam is horizontal, it is clear that the ball is not moving as a result of gravity. The gravitational force can be expressed as follows when the beam's horizontal angle rotates by angle $\emptyset$:

$$f_2 = mg\sin(\emptyset) \tag{5}$$

where g is the acceleration of gravity. Plugging Eq. (5) and Eq. (4) into Eq. (1) results into:

$$m\ddot{x} = mg\sin(\emptyset) - \frac{I_b}{r^2}\ddot{x} \tag{6}$$

Rearranged Eq. (6) gives:

$$\left(m + \frac{I_b}{r^2}\right)\ddot{x} = mg\sin(\emptyset) \tag{7}$$

As mentioned before, through the lever arm, the angle $\emptyset$ of the beam is driven. If the servo motor is positioned at an angle θ, the equation can be transformed using basic trigonometric principles, yielding the following result:

$$l\sin(\emptyset) = l_a\ \sin(\theta) \tag{8}$$

where l_a indicates the length of the lever arm and l represents the length of the beam. Substitutes Eq. (8) into Eq. (7) gives:

$$\left(m + \frac{I_b}{r^2}\right)\ddot{x} = \frac{mg\ l_a\sin(\theta)}{l} \tag{9}$$

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Rearranged Eq. (9) gives:

$$\ddot{x} = K_m \sin(\theta) \tag{10}$$

where $K_m = \frac{r^2 mg\, l_a}{l(r^2 m + I_b)}$

To finish the ball and beam system's dynamics, the motor model is needed. A well-examined mathematical model of a basic servo motor is provided by:

$$\tau\ddot{\theta} + \dot{\theta} = K_t V_{in} \tag{11}$$

where K_t is the motor constant, V_{in} is the input voltage to the motor, τ is the time constant of the motor, $\dot{\theta}$ is the angular velocity, and $\ddot{\theta}$ is the angular acceleration. Rearranged Eq. (11) gives:

$$\ddot{\theta} = -\frac{1}{\tau}\dot{\theta} + K_i V_{in} \tag{12}$$

where $K_i = \frac{K_t}{\tau}$

Let define the state system as follows: $[x_1 \quad x_2 \quad x_3 \quad x_4]^T = [x \quad \dot{x} \quad \theta \quad \dot{\theta}]^T$, and control input to the system $u = V_{in}$, the dynamic equation of the ball and beam system is given by the following differential equations:

$$\dot{x}_1 = x_2 \tag{13}$$

$$\dot{x}_2 = K_m \sin x_3 \tag{14}$$

$$\dot{x}_3 = x_4 \tag{15}$$

$$\dot{x}_4 = -\frac{1}{\tau}x_4 + K_i u \tag{16}$$

3. Proposed Controllers

The role of controller design is important whenever improving the performance of the system is required [28]-[30]. One of the biggest control problems is known as regulation, which requires all system states to gather into fixed points [31]. Because of the BnB system's instability, nonlinearity, and external disturbance, developing a control algorithm for the BnB system is no easy task [3]. To make the ball follow a reference input (x_r), the controller should be used to modify the beam's angle with a motor in order to manage the ball's position. An organized building of a control rule based on synergetic control (SC) and the state feedback controller (SFC) is presented in this section.

3.1. State Feedback Controller

The majority use of state feedback controllers (SFC) can be limited to two common control applications, which are regulation and trajectory tracking. By locating the system's closed-loop poles at desired positions, the requirements of controller design will be satisfied, and this is the main idea of SFC [32]. There are two limitations before implementing the SFC algorithm including the system's state needs to be measured and the system should be controllable [33]. To find the control law (u) of the SFC controller, the following formula is used:

$$u = k_1(x_r - x_1) + k_2 x_2 + k_3 x_3 + k_4 x_4 \tag{17}$$

The tuning gains of the SFC are mentioned as k_i $(i = 1,2,3,4)$ in Eq. (17). The block diagram of the SFC for the BnB system is shown in Fig. 2. Regardless of the simplicity of the SFC's structure, the tuning process plays a key role in the performance of the controller. In order to achieve the best performance, optimization, as will be discussed later, is employed to find the best value of the tuning gains of the SFC.

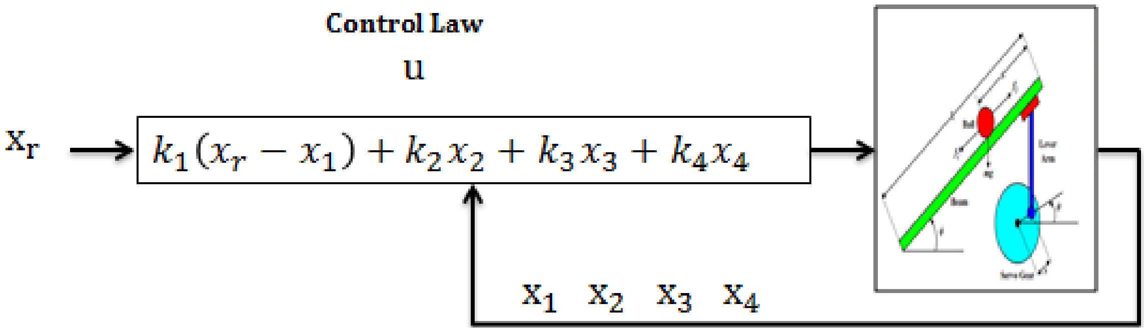

Fig. 2. Block diagram of SFC for BnB system

3.2. Synergistic Control

One of the reliable nonlinear control strategies for systems with nonlinearities in their dynamics that are susceptible to outside disturbances and model uncertainty is synergistic control (SC). SC controls the system's dynamics to go from any initial motion point into the manifold [34]-[37]. The procedure to design the control law based on the SC theory as follows [38]-[39]: The difference between the intended linear location x_r, and the actual position, x_1 , is what will be referred to tracking error, or e_1 while the tracking error e_2 as the difference between the desired angular position x_θ and the actual angular position x_3 as follows:

$$e_1 = x_r - x_1 \tag{18}$$

$$e_2 = x_\theta - x_3 \tag{19}$$

Taking the 1st and the 2nd derivatives of the errors gives:

$$\dot{e}_1 = \dot{x}_r - \dot{x}_1 \tag{20}$$

$$\ddot{e}_1 = \ddot{x}_r - \dot{x}_2 \tag{21}$$

$$\dot{e}_2 = \dot{x}_\theta - \dot{x}_1 \tag{22}$$

$$\ddot{e}_2 = \ddot{x}_\theta - \dot{x}_3 \tag{23}$$

Let define the marco-variable (φ) as a function of the errors e_1 and e_2 as follows:

$$\varphi = \dot{e}_1 + a_1e_1 + \dot{e}_2 + a_2e_2 \tag{24}$$

where a_1 and $a_2(a_1\text{and } a_2 > 0)$ are designing parameter. Taking the 1st derivative of the φ gives:

$$\dot{\varphi} = \ddot{e}_1 + a_1\dot{e}_1 + \ddot{e}_2 + a_2\dot{e}_2 \tag{25}$$

To guarantee the stability (i.e. ensure the state trajectories moves towards the desired manifolds and remain on it), lets define the following:

$$\dot{\varphi} + a_3\varphi = 0 \tag{26}$$

where $a_3(a_3 > 0)$ is an adjustable parameter represents the rate of convergence towards the desired manifolds. Applying the result of Eq. (25) in Eq. (26) gives:

$$(\ddot{e}_1 + a_1\dot{e}_1 + \ddot{e}_2 + a_2\dot{e}_2) + k_{sc}\varphi = 0 \tag{27}$$

Substitute Eq. (21) and (23) in Eq. (27) gives:

$$(\ddot{x}_r - \dot{x}_2 + a_1\dot{e}_1 + \ddot{x}_\theta - \dot{x}_3 + a_2\dot{e}_2) + a_3\varphi = 0 \tag{28}$$

Substitute Eq. (14), Eq. (16) in Eq. (28) gives:

$$\left(\ddot{x}_r - K_m \sin x_3 + a_1\dot{e}_1 + \ddot{x}_\theta + \frac{1}{\tau}x_4 - K_i u + a_2\dot{e}_2\right) + a_3\varphi = 0 \tag{29}$$

Solving Eq. (29) for u yields the following:

$$u = \frac{1}{K_i}\left(\ddot{x}_r - K_m \sin x_3 + a_1\dot{e}_1 + \ddot{x}_\theta + \frac{1}{\tau}x_4 + a_2\dot{e}_2 + a_3\varphi\right) \tag{30}$$

The block diagram of the SC for the BnB system is shown in Fig. 3.

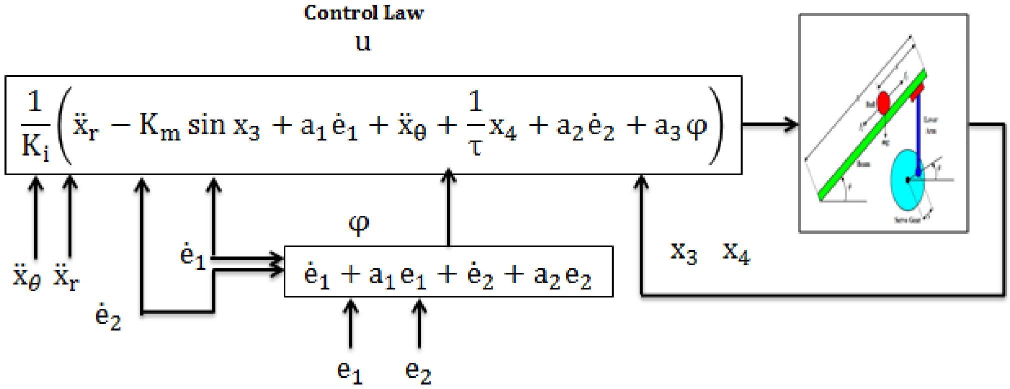

Fig. 3. Block diagram of SC for BnB system

4. Sea Lion Optimization

Selection of the controller's design variables greatly leverages its performance. Numerous researchers in controller design domains choose to use swarm optimization as a tool to determine appropriate controller parameters [40]-[44]. For this purpose, the sea lion optimization (SLO) is introduced in this paper. SLO is a swarm optimization algorithm inspired by the lifestyle of the sea for living and hunting prey. Sea lions are considered to be one of the smartest mammals, which imply their feature to assist them with allocating, surrounding, and attacking their prey [45]. The pseudo-code in Algorithm 1 provides the steps needed to execute the algorithm. Each stage has represented by a mathematical model that can be described as follow:

4.1. Detecting and Tracking Stage

The whiskers on sea lions are one of its most distinctive characteristics. The oval shape of sea lions' whiskers produced a highly sensitive indicator of size and position of the prey. There is a relation between whiskers direction and waves direction that the prey leaves behind them. If they are in the same direction the vibrations would be weak, therefore the sense of the preys' position would be feeble. A strong vibration would be produced in case that whisker direction is opposite to the waves direction which leads to powerful sense of the position. After identifying the location of the prey, the sea lion call others to join the group. This sea lion considered being the leader and the prey is the best current solution. The distance between the prey and sea lion can be represented in Eq. (31) [46].

$$\overrightarrow{Dist} = |\overrightarrow{2B} \cdot \overrightarrow{P(t)} - \overrightarrow{SL(t)}| \tag{31}$$

where $\overrightarrow{P(t)}$ is the position of target prey, $\overrightarrow{SL(t)}$ is the position of sea lion, B is current iteration multiplied by 2 to increase the space research. By increasing the iteration, the sea lion changes its position toward the target as in Eq. (32) [47].

$$\overrightarrow{SL(t+1)} = \overrightarrow{P(t)} - \overrightarrow{D_{lst}}.\vec{C} \tag{32}$$

where $(t+1)$ represents the next iteration, the parameter $\vec{C}$ range between 2 and -2 decreased linearly to drive the leader position.

Algorithm1: SLO's Pseudo-Code
1. Input
▪ Number of iteration T_{max}, Population size N_{pop}, Objective function
2. Initialization
▪ Initialize population N_{pop}
▪ Evaluate the objective function and select the best solution $\vec{P}$
3. Loop:
▪ **while** itr $< T_{max}$
• Compute $\overrightarrow{SP_{leader}}$ based on Eq. (33)
• **If** $\overrightarrow{SP_{leader}} < 0.25$
✓ Update the position using Eq. (36)
• **Else**
✓ **If** $\lvert\vec{C}\rvert < 1$
◆ Update the position using Eq. (32)
✓ **Else**
◆ Selected $\overrightarrow{SL_{rnd}}$ randomly
◆ Update the position using Eq. (38)
✓ **End if**
• **End if**
• **End for**
• Perform greedy selection and update $\vec{P}$
• t = t + 1
▪ **End while**
4. Print the Optimal Solution

4.2. Vocalization Stage

When the sea lion detects the prey, it sends sounds to call others that are on the shore and others that are in the water. The speed of moving sound inside the water is faster than those in the water therefore, there are different speed of sound as it's reflected in different medium that can represented as $\vec{V}_1$ for the speed in water and $\vec{V}_2$ for the speed in air. Sea lions have small ears that enable them from hearing the call inside and outside the water. The sea lions gather to chase the prey and surround them to start attacking. The speed sound of the sea lion leader can be represented in Eq. (33) [48].

$$\overrightarrow{SP_{leader}} = \left| \left(\vec{V}_1(1+\vec{V}_2)\right) / \vec{V}_2 \right| \tag{33}$$

$$\vec{V}_1 = \sin\ \theta \tag{34}$$

$$\vec{V}_2 = \sin\ \emptyset \tag{35}$$

4.3. Attacking and Exploration Stage

The target prey is allocated by the leader, who informs others about the location and leads the group to hunt toward it. It can be established from equation (32), as the parameter $\vec{C}$ decrease the best search agent, which is the leader close to the best current solution, which is the prey. Therefore, the location is updated every time the search agent is moved to the prey. In case $\vec{C}$ is greater than 1 the algorithm works globally. In other words, a random search agent is selected to find the best solution. While if $\vec{C}$ is less than -1 means the search agent changes its location. Another member of the sea lion can diagnose better prey to become the new search agent hunting for the current best solution. The sea lions begin to hunt the prey from the edge after surrounding them. This can be represented in Eq.s (36)-(38) [48].

$$\overrightarrow{SL}(t+1) = |\vec{P}(t) - \overrightarrow{SL}(t)| \cdot \cos(2\pi m) + \vec{P}(t) \tag{36}$$

$$\overrightarrow{D\imath St} = \left|\overrightarrow{2B} \cdot \overrightarrow{SL}_{rnd}(t) - \overrightarrow{SL(t)}\right| \tag{37}$$

$$\overrightarrow{SL}(t+1) = \overrightarrow{SL}_{rnd}(t) - \overrightarrow{D\imath st} \cdot \vec{C} \tag{38}$$

where $|\vec{P}(t) - \overrightarrow{SL}(t)|$ is the distance between the best solution and the search agent. The terms $\cos(2\pi m)$ indicate the circle shape of sea lions surrounding the ball of prey where m is a random number in [-1, 1]. The term $\overrightarrow{SL}_{rnd}(t)$ represents search agents that have been selected randomly. In Eq.s (37) and (38), the algorithm works to find a global optimal solution.

5. Results and Discussion

This section presents the simulated results obtained within the MATLAB environment to demonstrate the efficiency of the suggested SC. Through simulation, a performance comparison between this proposed SC and the classical SFC is carried out and analyzed. The dynamic equations of the system as provided by Eq.s (13)-(16) are used to simulate the system. A step input is employed to evaluate the proposed SC to move the ball on the beam for a 0.03m. Table 1 lists the system's model parameter values [11].

Table 1. Parameters of BnB system

Parameters	Value	Unit
Mass of the ball (m)	0.064	k_g
Radius of the ball (r)	0.0127	m
Length of the beam (l)	0.4255	m
Length of the lever arm (l_a)	0.0254	m
Inertia of the ball (I_b)	4.13×10^{-6}	$k_g m^2$
Acceleration of gravity (g)	9.81	ms^{-2}
Time constant of the motor (τ)	0.0248	s
Motor constant (K_t)	0.0379	NmA^{-1}

Eq. (39) provides the Integral Time of Absolute Errors (ITAE) [49]-[50] which is employed by the SLO as an objective function to adjust the design parameters of the suggested SC and the traditional SFC.

$$ITAE = \int_{tt=0}^{tt=t_{sim}} tt|e(t)|dt \tag{39}$$

where e is the tracking error and t_{sim} refers the total simulation time. The number of SLO iterations and population size are chosen to be 30 and 50, respectively. In Fig. 4, the convergence of the SLO is seen. Table 2 lists the optimum values for the design parameters based on SLO for the suggested SC as well as the traditional SFC.

Fig. 5 show the responses of linear position and velocity of the ball and angular position and velocity of the lever arm of the BnB system controlled by the SC and the SFC. Error steady state ($e_{s.s}$), settling time (t_s), maximum overshoot (σ_o), and ITAE index are used to assess the system's performance. Table 3 reports the dynamic performance of the two controllers for angular and linear responses. The two controllers can successfully regulate the system with zero $e_{s.s}$ when the two control techniques (SFC and SC) are compared using Fig. 5, Table 3. It is also proven by the findings that the SC tracks the target output more quickly than the SFC. The SC reduces the value of t_s from 27 s based on the SFC to 9 s for the SC. Moreover, the SC reduces the ITAE index to 344 as compared to 811.2 for the SFC.

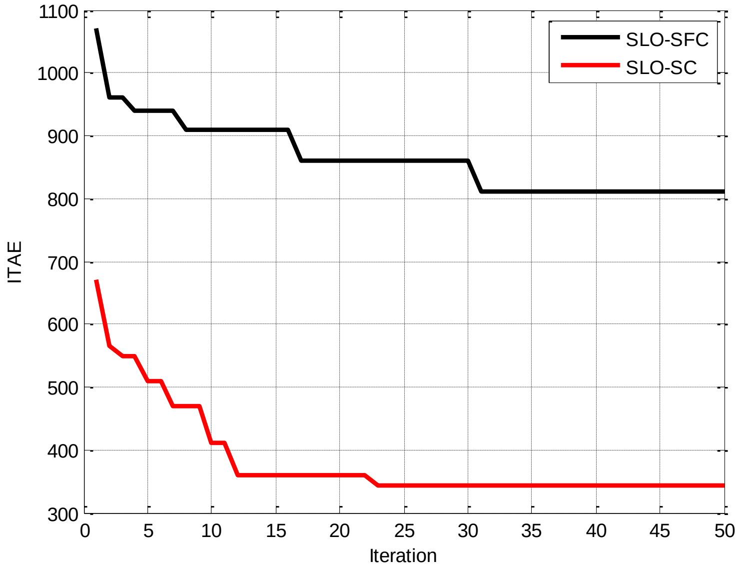

Fig. 4. Convergence of SLO

Table 2. Optimal controller's design

Controller	Parameter	Value
SFC	$\boldsymbol{k_1}$	15
	$\boldsymbol{k_2}$	-50
	$\boldsymbol{k_3}$	-70
	$\boldsymbol{k_4}$	-20
SC	$\boldsymbol{a_1}$	0.2
	$\boldsymbol{a_2}$	0.8
	$\boldsymbol{a_3}$	20

Table 3. Specification performances of the system's linear and angular position

Controller	Controlled variable	$t_s(s)$	$e_{s.s}(m)$	$\sigma_o(\%)$	ITAE
SFC	x_1	27	0	16.6	811.2
SC		9	0	1	344
SFC	x_3	3.05	0	3.25	199.7
SC		2.85	0	2.95	107.1

Additionally, the σ_o value is reduced from 16.6% for the SFC to 1% for the SC. In terms of the angular position response, the SC reduces the value of t_s from 3.05 s based on the SFC to 2.85 s for the SC. Moreover, the SC reduces the ITAE index to 107.1 as compared to 199.7 for the SFC. Additionally, the σ_o value is reduced from 3.25% for the SFC to 2.95% for the SC.

To evaluate the robustness of the SC to handle external disturbance, the simulation has run for 50 seconds, then a step external perturbation has been applied to each controller. The reaction of the two controlled systems to an outside perturbation is illustrated in Fig. 6. Time recovery (t_{rec}), error steady state ($e_{s.s}$), and the difference between the highest and minimum amplitude of the response under disturbance (δ) are used to assess the performance of the system with disturbance. Table 4 reports the two controllers' dynamics performance for both linear and angular response with disturbance.

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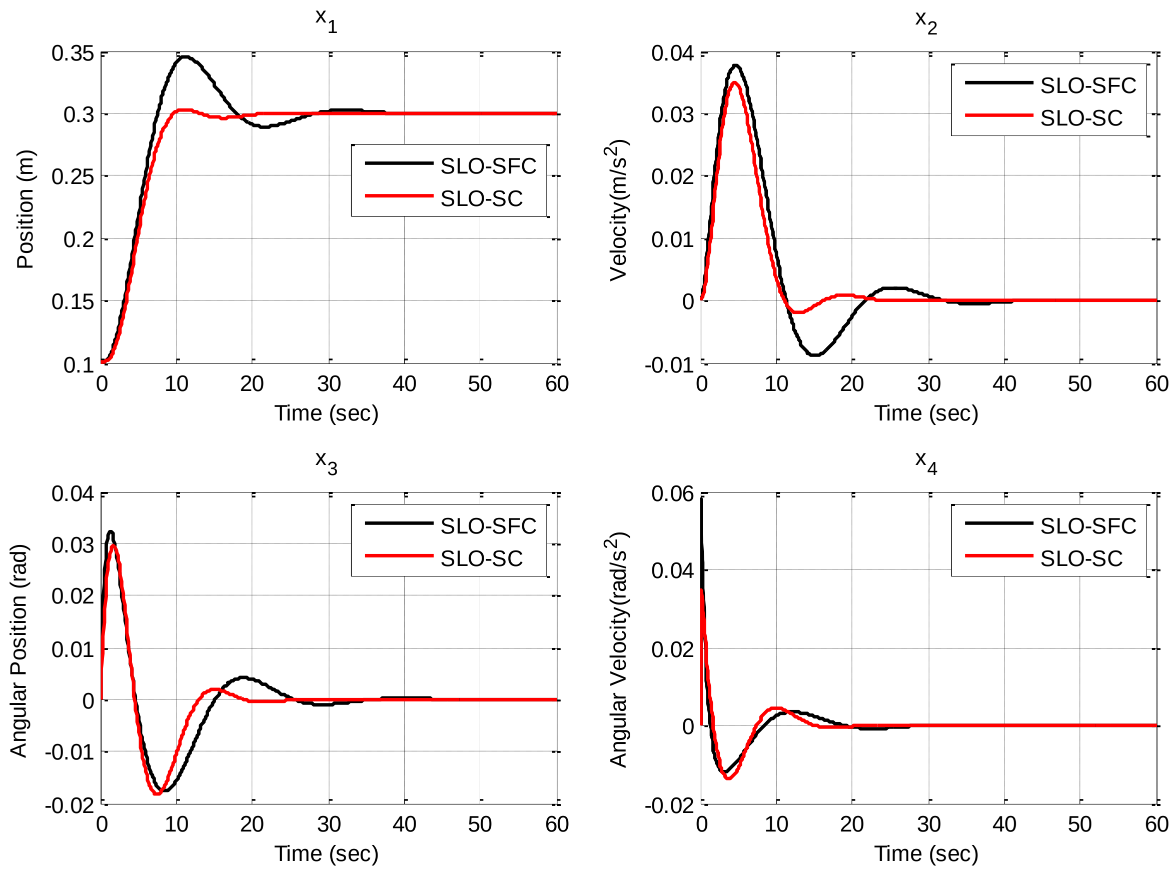

Fig. 5. Responses of system

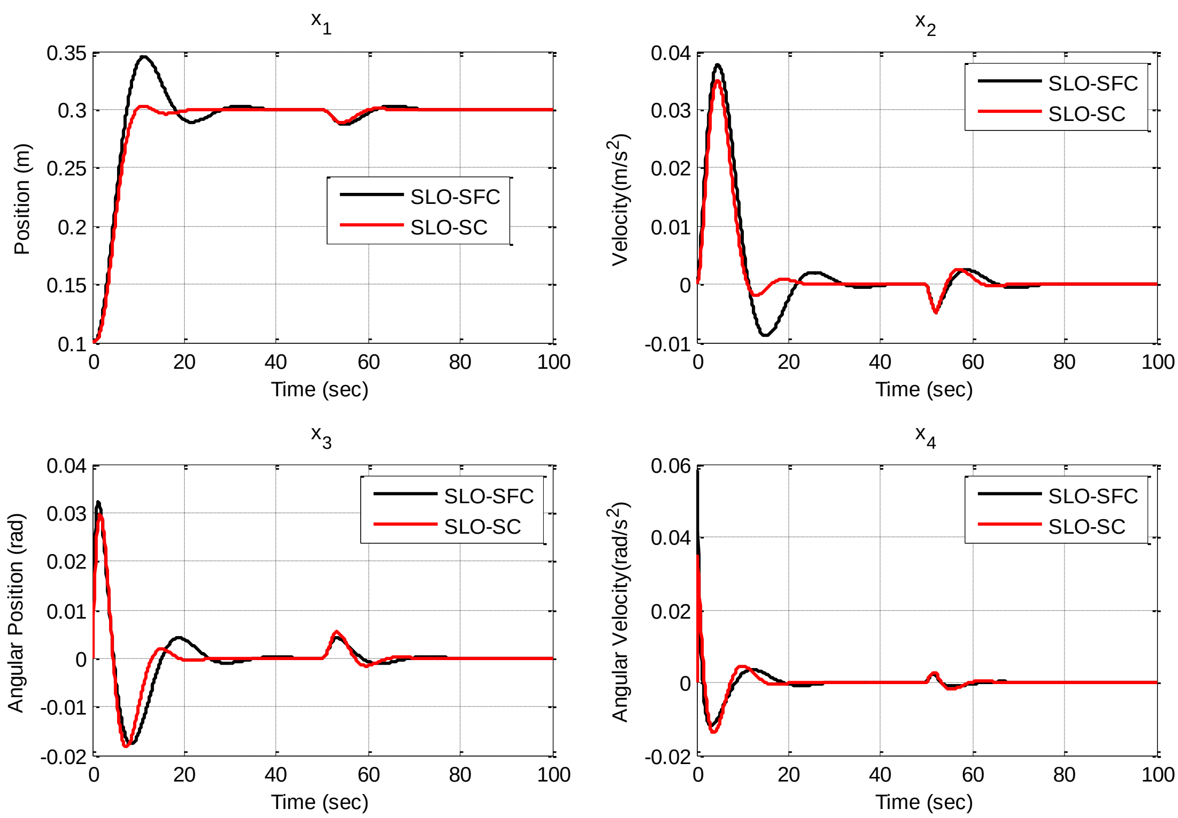

Fig. 6. Responses of the system with disturbance

It is clear from comparing the two control strategies (SFC and SC) based on Fig. 6 and Table 4 that the two controllers can successfully regulate the system with zero $e_{s.s}$ whenever an external disturbance occurs. The results also show that the SC has a more robustness response than the SFC. The SC reduces the value of t_{rec} from 22 s based on the SFC to 15 s for the SC. Besides, the δ value is reduced from 0.016 for the SFC to 0.011 for the SC. In terms of the angular position response, the SC reduces the value of t_{rec} from 28 s based on the SFC to 20 s for the SC. Furthermore, the δ value is reduced from 6.96 for the SFC to 5.41 for the SC. This leads to conclusion that the SC is more robust against external disturbance than SFC.

Table 4. Specification performances of the system's linear position with disturbance

Controller	Controlled variable	$t_{rec}(s)$	$e_{s.s}(m)$	$\delta(\%)$
SFC	x_1	22	0	0.016
SC		15	0	0.011
SFC	x_3	28	0	6.96
SC		20	0	5.41

6. Conclusion

The procedure to design a synergetic control (SC) for ball and beam position tracking control has been addressed in this paper. To demonstrate the efficiency of the suggested SC, a simulation based on the MATLAB platform was used to compare its results with the classical state feedback controller (SFC). To improve the controllers' performance, the design parameters were optimized using the sea lion optimization (SLO). The results of the simulations demonstrated that, for step input tracking, the suggested SC provides superior transient characteristics in terms of improvements in settling time, overshoot and ITAE than the traditional SFC. Furthermore, SC exhibits more resistance to external disturbance that SFC. In future work, the robustness parameters uncertainties should be considered in the formulation of the control law. Besides, this study can be extended for future work by considering other control techniques.

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