

Inverted pendulum systems, such as double or single, rotational or translational inverted pendulums are non-linear and unstable, which have been the most dominant approaches for control systems. The double inverted pendulum is one kind of a non-linear, unstable system, multivariable, and strong coupling with a wide range of control methods. To model these types of systems, many techniques have been proposed so that motivating researchers to come up with new innovative solutions. The Linear Quadratic Regulator (LQR) controller has been a common controller used in this field. Meanwhile, the Artificial Bee Colony (ABC) technique has become an alternative solution for employing Bee Swarm Intelligence algorithms. The research solutions of the artificial bee colony algorithm in the literature can be beneficial, however, the utilization of discovered sources of food is ineffective. Thus, in this paper, we aim to provide a double inverted pendulum system for stabilization by selecting linear quadratic regulator parameters using a bio-inspired optimization methodology of artificial bee colony and weight matrices Q and R . The results show that when the artificial bee colony algorithm is applied to a linear quadratic regulator controller, it gains the capacity to autonomously tune itself in an online process. To further demonstrate the efficiency and viability of the suggested methodology, simulations have been performed and compared to conventional linear quadratic regulator controllers. The obtained results demonstrate that employing artificial intelligence (AI) together with the proposed controller outperforms the conventional linear quadratic regulator controllers by more than 50 % in transient response and improved time response and stability performance

Keywords: double inverted pendulum (DIP), non-linear systems, unstable systems, linear quadratic regulator (LQR) controller, artificial bee colony (ABC)

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1. Introduction

In the control systems theory subject, one of the most notable equipment pieces is the Inverted Pendulum System (IPS). For control instructions or research reasons, it is cheap and easy to construct and install in laboratories. One of the non-linear problems is the inverted pendulum system, which is studied by many academicians, most of them using linearization theory control systems [1]. Controlling this system via traditional means is, in general, a difficult process. Since it is a non-linear issue with two degrees of freedom, such as inverted pendulum angle and cart location, and only one control input, this is the case. One of the excellent models for attitude control of a satellite and a space booster rocket is the Inverted Pendulum, in addition to aircraft stabilization in turbulent airflow, an automatic aircraft landing system, and ship cabin stability [2]. There are several options for solving such an issue with a non-linear time variant system like linear quadratic regulator LQR, in addition to including linearization or real-time computer simulation [3].

Hence, Artificial Intelligence (AI) has been involved to assist in modeling the aforementioned system while delivering the highest level of stability in appropriate time.

For instance, Artificial Bee Colony (ABC) was invented in 2005 as one of the most recently defined algorithms inspired by honeybee intelligence [4]. It is as simple as Differential Evolution (DE) and Particle Swarm Optimization (PSO) algorithms and employs only basic control parameters like maximum cycle number and colony size. As an optimization tool, ABC offers a population-based search technique in which artificial bees modify individuals called foods positions over time, with the goal of the bees discovering high nectar-producing food sources and last but not least, the one with the most nectar [5, 6].

According to all mentioned above, the double inverted pendulum is one kind of a non-linear, unstable system, multivariable, and strong coupling with a wide range of control methods and the conventional linear quadratic regulator LQR controller is the optimal solution for controlling these types of control systems. This has been the trend for dealing with general industrial engineering. Therefore, research on the development of an inverted pendulum is a type of mechanical system that is used to demonstrate control theory. It consists of a mass attached to the end of a lever, which is mounted upside down and kept in an unstable equilibrium. It is possible to stabilize the system using feedback control sys-

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LQR CONTROLLER DESIGN FOR STABILIZATION OF NON-LINEAR DIP SYSTEM BASED ON ABC ALGORITHM

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tems, such as PID controllers, by providing an input torque or force that counteracts the effects of gravity. This type of system has applications in robotics, aerospace engineering, and automotive engineering.

2. Literature review and problem statement

In the literature, various mathematical approaches for optimizing the settings of a non-linear double inverted pendulum system have been proposed. These scholarly studies have introduced algorithms or mathematical models to accurately control the DIP system. In [7], the PID and LQR have been applied to the mathematical model of the double inverted pendulum system, the results validate and show the advantage of the LQR strategy over the PID controller. Many control techniques are used to control the double inverted pendulum system and the results show that the LQR controller is more effective and robust [8]. Another research study [9]; presents the LQR sliding surface-based Sliding Mode Controller (LQR–SMC), which was applied for balancing control of a non-linear DIP system. The presented LQR provides acceptable system stability under external disturbances but the LQR optimal gains are needed for designing the sliding surface in SMC. Likewise, the linear quadratic Gaussian LQG optimal control was suggested, whereas, the system could be affected by noise. The results show that the designed controller dominates the non-linear double inverted pendulum system and provides excellent noise reduction and anti-interference ability [10].

On the other hand, in [11], the mixed sensitivity H1, H2, and H-infinity controllers were applied to balance the rotary double inverted pendulum system. These controllers were proposed to improve the robust stability and enhance the time response performance of the system compared to the LQR controller. The results show high performance of the implemented controllers on the non-linear double inverted pendulum, so both techniques show improvement in transient response, robust stability, and disturbance rejection, but the LQR controller gives a better robust performance as compared to H controllers. Additionally, in [12], a state-feedback design controller was presented for stabilizing the two-wheeled inverted pendulum (TWIP) system. The results showed that the proposed controller realized a minimum deviation for the pendulum angle without giving a satisfactory response for controlling the pendulum cart position. Similarly, the H-infinity controller was presented to enhance the inverted pendulum system performance [13]. The obtained results showed that the step response for the proposed H-infinity controller has a relevant settling and rise time, and unsatisfactory percentage overshoot.

A novel algorithm, called UniNeuro, that integrates neural networks with the uniform design and genetic algorithms was proposed in [14]. The proposed method has been applied on a non-linear double inverted pendulum DIP model. The complexity of the proposed method raises from the need for more than 25 training data items and more than 20 optimized simulation results to swing-up and standing on the robust stability of the DIP system. However, due to its principles, it is a highly unstable non-linear and open loop system, causing the pendulum to quickly fall on anytime. Due to the failure of traditional linear approaches to imitate the system non-linear dynamics, the system is simulated [15].

As a result, the previous conventional approaches cannot realize an optimized solution for either the response or stabilization of a non-linear DIP model. Thus, an alternative good solution can be achieved versus employing the LQR controller parameters to control the DIP system. In this paper, first we utilized the LQR controller to model the system. Then the ABC algorithm was combined with LQR to assist the system in accurately guiding the reach stabilization. A comprehensive comparison was carried out to evaluate both suggested controllers to highlight the most suitable one in terms of better response and stabilization.

3. The aim and objectives of the study

The aim of this study is to realize an optimized solution for either the response or stabilization of a non-linear double inverted pendulum DIP model.

To achieve this aim, the following objectives are accomplished:

- to model these types of systems;
- to present a conventional linear quadratic regulator (LQR) controller to stabilize double inverted pendulum systems;
- to propose an ABC-LQR controller to achieve stability at a reduced time response for DIP systems;
- to compare the results of the proposed ABC-LQR controller with the conventional LQR controller.

4. Materials and methods of research

First we utilized the conventional LQR controller to model the system. Then the ABC algorithm was combined with LQR to assist the system in accurately guiding the reach stabilization. A comprehensive comparison was carried out to evaluate both suggested controllers to highlight the most suitable one in terms of better response and stabilization.

4.1. Double inverted pendulum model

Electrical measuring devices, transmission belts, pulleys, motors, rails, and control object are the system key components of the presented double inverted pendulum model. The overall structure is given in Fig. 1. An inverted pendulum state-space equation is as follows [8]:

$$\begin{bmatrix} \dot{y}_1 \\ y_2 \\ \dot{y}_3 \\ y_4 \\ \dot{y}_5 \\ y_6 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1.6224 & 0 & 0.1803 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 54.5719 & 0 & -25.6635 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -76.9906 & 0 & -67.3545 & 0 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \end{bmatrix} + \begin{bmatrix} 0 \\ 0.3902 \\ 0 \\ -1.0033 \\ 0 \\ 0.3344 \end{bmatrix} u, \quad (1)$$

$$z(t) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} y1 \\ y2 \\ y3 \\ y4 \\ y5 \\ y6 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} u(t). \tag{2}$$

The automobile, the higher pendulum, and the lower pendulum make up the control object. The top and lower pendulums are joined by a hinge, whilst by another hinge the lower pendulum is attached to the car. The car can only travel to the left or right and freely drive along the two parallel tracks, while the top and lower pendulum bars can only tilt to the right or left. As a point of comparison, the car employs the rail's center [16–18].

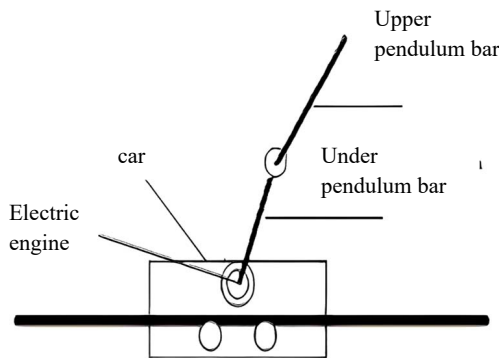


Fig. 1. The double inverted pendulum basic structure

Usually, the double inverted pendulum (DIP) systems are non-linear and unstable, which are the most dominant approaches for control systems. The most commonly used controller to stabilize the DIP is the Linear Quadratic Regulator (LQR) controller. Meanwhile, the Artificial Bee Colony (ABC) technique has become an alternative solution by employing Bee Swarm Intelligence algorithms.

4. 2. Linear quadratic regulator controller

Fig. 2 depicts a full-state feedback for a double inverted pendulum controller with a reference input [19, 20]. Assume that the state equation of a linear time-invariant system is:

$$\dot{x} = Ax + Bu, \tag{3}$$

$$\dot{y} = Cx + Du.$$

And the index function of quadratic performance is

$$J = \frac{1}{2} \int_0^t [X^T(t)Q(t)X(t) + U^T(t)R(t)U(t)]dt. \tag{4}$$

When an optimal feedback control law is found that allows J to be reduced to a minimum, this is referred to as optimal control. The optimal control law, according to optimal control theory, that permits equation (3) to be reduced to its smallest value is:

$$u(t) = -R^{-1}B^T\lambda(t), \tag{5}$$

$\lambda(t)$ can be calculated using the formula below.

$\lambda(t) = -p(t)X(t)$, $p(t)$ is the Riccati differential equation solution:

$$\dot{p}(t) = -p(t)A - A^T p(t) + p(t)BR^{-1}B^T p(t) - Q.$$

When $t \rightarrow \infty$, $P(t)$ tends to be a matrix with a constant value, and $\dot{p}(t) = 0$, so:

$$pA + A^T p - pBR^{-1}B^T p + Q = 0. \tag{6}$$

Riccati matrix algebraic equation is the name of this equation. As a result, the following state feedback vector can be obtained:

$$K = -R^{-1}B^T p. \tag{7}$$

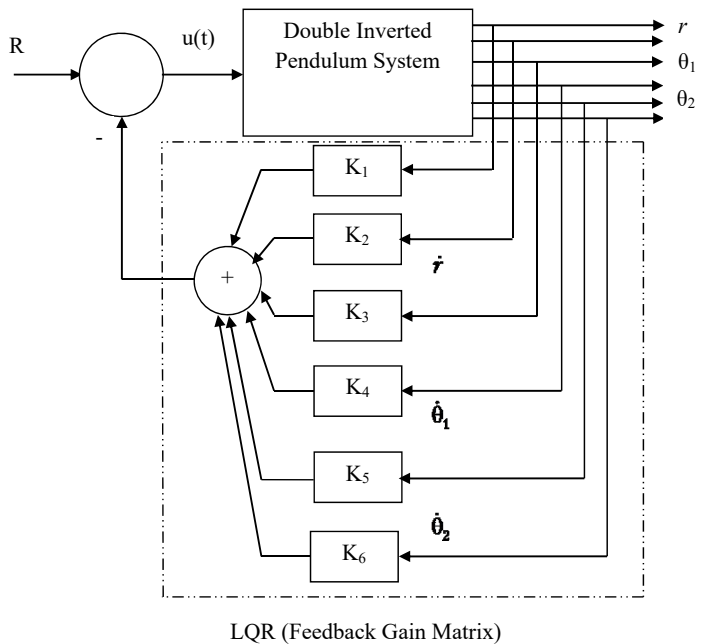


Fig. 2. Double inverted pendulum controller with reference input

All mentioned above demonstrates that the key to designing an optimal controller is the proper selection of weighting matrices R and Q, computing the Riccati matrix algebraic equation P, and next solving the feedback gain K [15].

4. 3. Proposed artificial bee colony algorithm

In the Bees Algorithm, the artificial bee colony is made up of three types of bees: scouts, bystanders, and hired bees. The hired artificial bees make up half of the colony, while bystanders make up the other half. For each food source, there is only one utilized bee. In other words, the number of engaged bees is proportional to the amount of food sources in the immediate vicinity of the hive. After the food source is abandoned by the bees, the utilized bee becomes a scout. The nectar amount of a food source refers to the related solution quality (fitness), and the food source position reflects a feasible solution to the optimization problem [21, 22]. The artificial BA initialization steps (pseudo-coding):

1. Initialize the solutions population x_i, j , with $i=1 \dots SN$ (where SN is the number of food sources) and $j=1 \dots D$ is the dimension of the problem. For LQR optimization (namely $q_1, q_2, q_3, q_4, q_5, q_6$ and R), $D=7$.
2. Evaluate the population.
3. Cycle=1.

4. Repeat.
5. Create new solutions x_i, j for the utilized bees by using (4) and evaluate them.
6. Use the greedy selection method.
7. Determine the probabilities P_i, j for the solutions x_i, j by (4&3).
8. Depending on P_i, j , the new solutions x_i, j producing for the on looking from the solutions x_i, j selected and evaluate them.
9. Apply the greedy selection process.
10. Determine the scout abandoned solution, if exists, and replace it with a new randomly produced solution x_i, j by (4&5).
11. Memorize the best solution that came up with so far.
12. Cycle=Cycle+1.
13. Until Cycle=MCN (Maximum Cycle Number).

4. 4. Proposed ABC-LQR controller

The best controller parameters and weight matrices R and Q are discovered by using the ABC method for a favorable output response from the controlled system. A decent set of control parameters ($q_{11}, q_{22}, q_{33}, q_{44}, q_{55}, q_{66}, R$) can obtain an excellent output response for the system, resulting in the minimization of time domain performance criteria such as steady state error (e_{ss}), maximum overshoot (percent MP), rise time (t_r), and settling time (t_s). Fig. 3 shows the ABC-LQR controller for a double inverted pendulum. The fitness function that has been proposed for the optimization of ABC-LQR controller parameters is as follows:

$$F = W_{max} * (1 - \exp(-v)) * (MP + Ess) + w_{min} * \exp(-1) * (ts - tr),$$

where Ess – steady state error; ts – settling time; tr – rise time; MP – maximum overshoot; w_{min} – minimum inertia weight; w_{max} – maximum inertia weight.

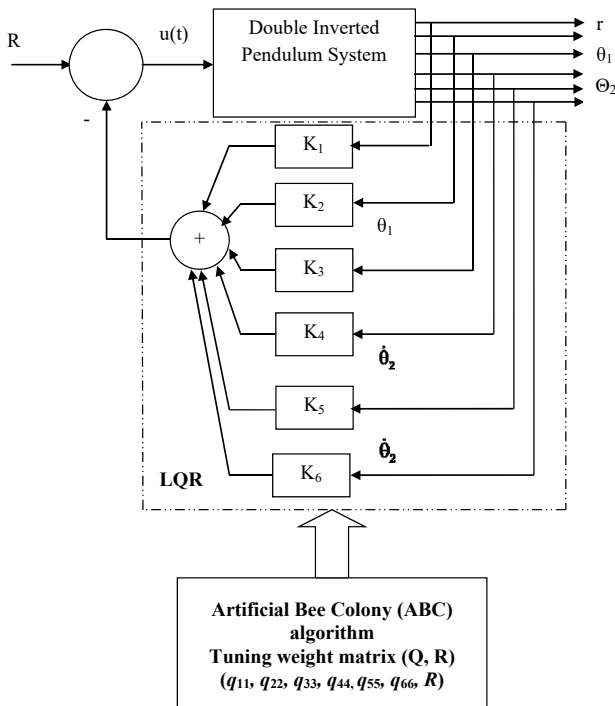


Fig. 3. Block diagram of the double inverted pendulum ABC-LQR controller

To obtain an excellent output response for the double inverted pendulum system, this paper uses the artificial bee colony ABC technique to assign values of the linear quadratic regulator LQR controller parameters ($q_{11}, q_{22}, q_{33}, q_{44}, q_{55}, q_{66}$ and R).

5. Results of the proposed ABC-LQR and conventional controllers

5. 1. Simulation parameters and step response

The ABC method is used to simulate a double inverted pendulum system. Moreover, the results of the simulation are presented and compared to the LQR controller [16]. Table 1 shows the values of the parameters used in the MATLAB environment to execute the ABC algorithm.

Table 1

Values of ABC parameters

Parameter	Value
Number of particles	20
Maximum number of iterations	100
C1(Cognitive component)	2
C2 (Social component)	2
Velocity (Maximum value)	10
Inertia Weight (Minimum value)	0.4
Inertia Weight (Maximum value)	0.9

Using ABC-LQR and conventional LQR controllers, Fig. 4–6 present the step response of pendulum angles and cart position.

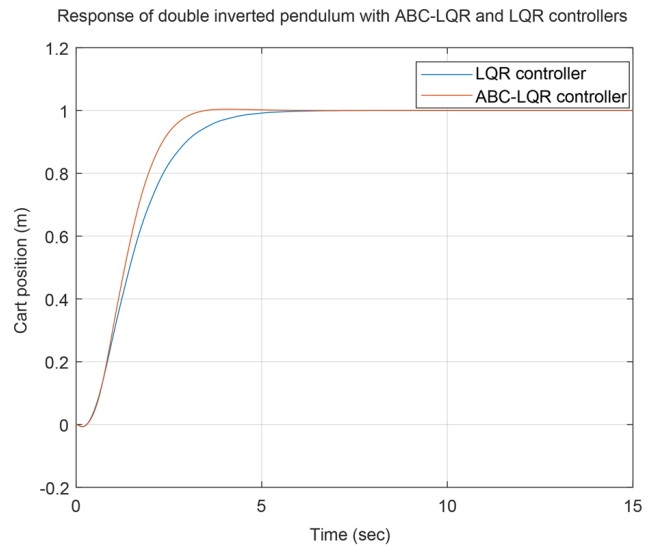


Fig. 4. Cart position step response using ABC-LQR and conventional controllers

From Fig. 4–6, the results obtained from the proposed ABC-LQR controller outperformed the results from the conventional LQR controller according to the compared pendulum step response (angle 1, angle 2, and cart position).

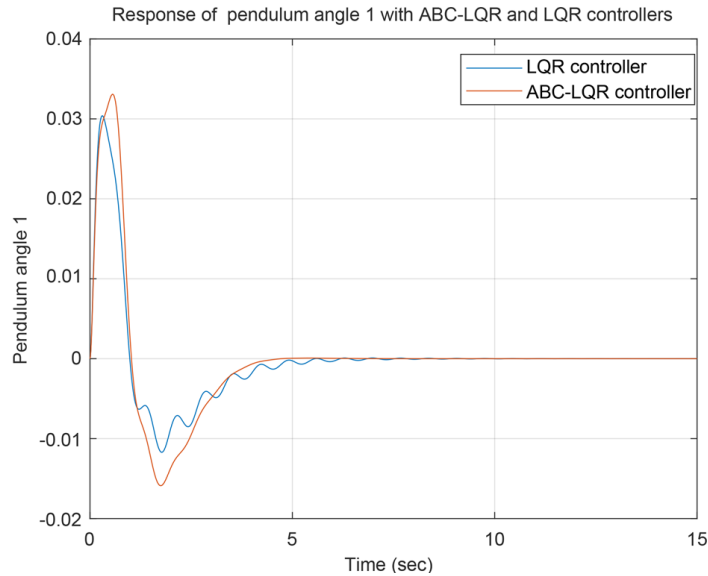


Fig. 5. Pendulum angle 1 step response using ABC-LQR and conventional controllers

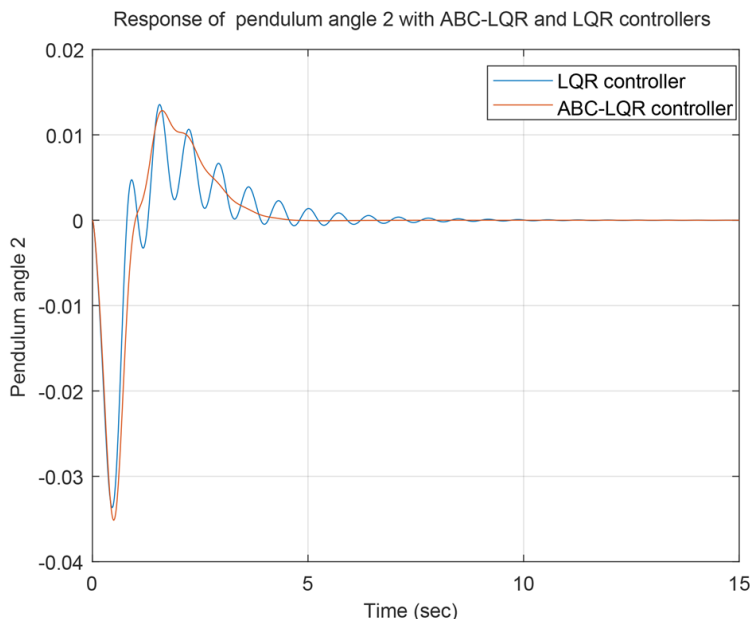


Fig. 6. Pendulum angle 2 step response using ABC-LQR and conventional controllers

5. 2. Generation of linear quadratic regulator parameters

The values of q_{11} , q_{22} , q_{33} , q_{44} , q_{55} , q_{66} and R for each gain, convergence curve is referred to as a particle, and it is drawn to show how the artificial bee colony converged to its ultimate value. Fig. 7 illustrates the artificial bee colony algorithm combining through generations for selecting the linear quadratic regulator parameters (R and $q_{11}-q_{66}$).

Fig. 8 depicts the control law $u(t)$ of ABC-LQR and conventional LQR controllers.

From Fig. 8, the results obtained from the proposed ABC-LQR controller outperformed the results from the conventional LQR controller according to the compared control law u step response.

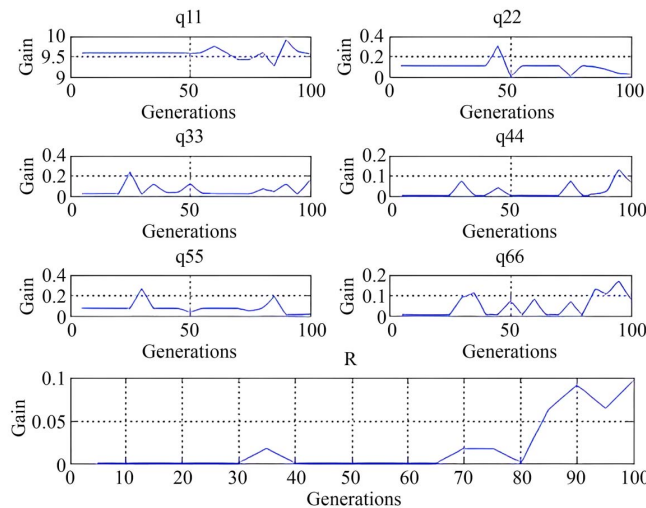


Fig. 7. Artificial bee colony algorithm converging through generations

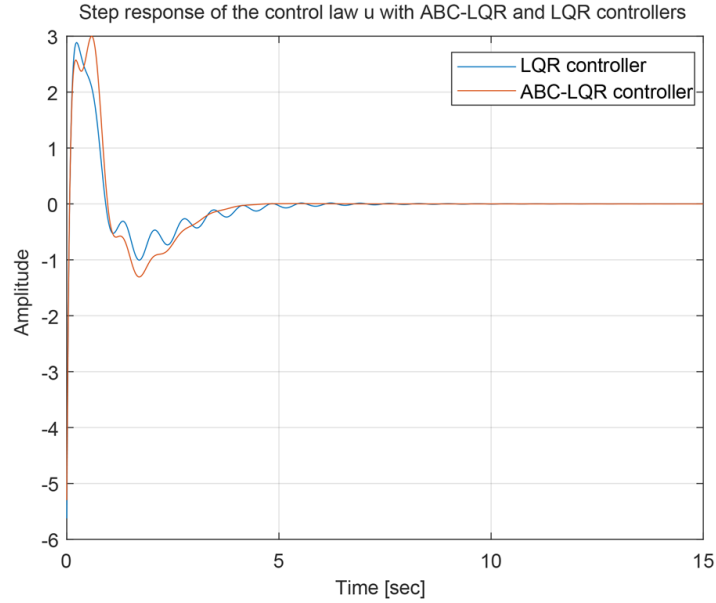


Fig. 8. Control law u step response using ABC-LQR and conventional controllers

5.3. Proposed controller gain matrix and closed loop poles

The ABC-LQR controller parameters R and Q are:

$$Q = \begin{bmatrix} 9.61063 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.104672 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0141357 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.00219181 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0657369 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.00371863 \end{bmatrix}$$

$R = [0.0013793]$.

The LQR controller parameters Q and R are taken from reference [16] for comparison:

$$Q = \begin{bmatrix} 18.6273 & 0 & 0 & 0 & 0 & 0 \\ 0 & 17.6791 & 0 & 0 & 0 & 0 \\ 0 & 0 & 47.5438 & 0 & 0 & 0 \\ 0 & 0 & 0 & 30.5754 & 0 & 0 \\ 0 & 0 & 0 & 0 & 57.0113 & 0 \\ 0 & 0 & 0 & 0 & 0 & 16.56 \end{bmatrix}$$

$R = [0.589]$.

Table 2 shows the elements of the gain matrix K produced using ABC-LQR and conventional LQR controller.

Table 2

Gain matrix K

Gain [K]	ABC-LQR controller	Conventional LQR controller
K1	-83.4732	-5.6237
K2	-43.7983	-9.3242
K3	-333.1715	-217.6097
K4	-39.4992	-23.6103
K5	53.1085	-7.4510
K6	8.9778	6.0522

Table 3 shows the closed loop poles for the ABC-LQR and conventional LQR controllers.

Table 3

Closed loop poles [P]

Closed loop poles [P]	ABC-LQR controller	Conventional LQR controller
P1	-16.3329	-12.8968
P2	-1.6497+9.8402i	-0.5215+9.062i
P3	-1.6497-9.8402i	-0.5215-9.062i
P4	-2.8741+1.6949i	-1.4336+0.1598i
P5	-2.8741-1.6949i	-1.4336-0.1598i
P6	-2.4185	-5.2666

Tables 2, 3 showed that each of the six criteria for the proposed ABC-LQR controller gets an identified closed loop pole and an optimal gain after executing the artificial bee colony algorithm.

5.4. Performance characteristics of the proposed controller

Tables 4–6 show the time response specifications of the system under study when fitted with the proposed controller.

Table 4

Cart position performance characteristics

Specifications of time response	ABC-LQR controller	Conventional LQR controller
Settling time Ts, sec	2.26	4.29
Rise time Tr, sec	1.2	2.33
Overshoot M, %	0	0.000749
Steady state error ess	0	0

From Tables 4–6, the results obtained from the proposed ABC-LQR controller outperformed the results from the conventional LQR controller according to the compared transient response (rise time and settling time).

Table 5

Pendulum angle (1) performance characteristics

Specifications of time response	ABC-LQR controller	Conventional LQR controller
Settling time T_s , sec	2.97	5.3
Rise time T_r , sec	0.063	0.0304
Overshoot M , %	0	0

Table 6

Pendulum angle (2) performance characteristics

Specifications of time response	ABC-LQR controller	Conventional LQR controller
Settling time T_s , sec	2.83	5.79
Rise time T_r , sec	0.0645	0.0336
Overshoot M , %	0	0

6. Discussion of the experimental results of the proposed controller

This work proposes an improved double-inverted pendulum system that employs the ABC-LQR controller rather than the conventional LQR. The gain matrix $[K_1-K_6]$ and the closed loop poles $[P_1-P_6]$ for the proposed LQR controller are shown in Tables 2, 3 respectively. As shown in Fig. 4–6, the results obtained from the proposed ABC-LQR controller outperformed the results from the conventional LQR controller according to the compared step response of the pendulum (angle 1, angle 2, and cart position). Moreover, the experimental results (Table 4) showed that the settling time for the double inverted pendulum cart position is 2.26 and 4.29 sec., meanwhile the rise time is 1.2 and 2.33 sec., and the maximum percentage overshoot is 0 and 0.000749 % for the proposed and conventional controller, respectively. Thus, the proposed ABC-LQR controller gives an improved transient response of more than 50 % compared to the conventional linear quadratic regulator controller. This point is also revealed in the performance of double inverted pendulum angles (1 and 2) shown in Tables 5, 6. On the other hand, the steady-state error has been eliminated in both proposed and conventional controllers.

In brief, the proposed ABC-LQR provides a better time response (percentage overshoot, rise time, and settling time), which in return enhanced the double inverted pendulum controlling operation. This includes the improvement of the cart position, under the pendulum bar (angle 1), and the upper pendulum bar (angle 2). Basically, this work focuses on the presentation of an ABC-LQR controller that deals with the double inverted pendulum system. Unlike the previous research work, which mainly considered the LQR controller, in this work, we investigated the implementation of the ABC-LQR and compared the obtained results with that of the LQR controller. The achieved results have demonstrated that the proposed ABC-LQR controller attained improved time-response and stability performance. Without the loss of generality, the ABC-LQR controller incurs more computational time due to the number of iterations needed to get the LQR parameters. Consequently, this work shows the tradeoff between improved performance and increased complexity.

The limitations of LQR controller design for the stabilization of a nonlinear DIP system based on the ABC

algorithm must be considered when applying the proposed solution in practice, including:

- model inaccuracies: The LQR controller design assumes that the model used to describe the system is accurate. In practice, it is often difficult to obtain an accurate model of a complex system, especially when dealing with nonlinear systems;

- computational complexity: The ABC algorithm used in the proposed solution can be computationally expensive, particularly for large systems with many state variables. This can limit the real-time applicability of the controller;

- sensitivity to disturbances: The LQR controller is designed to stabilize the system under ideal conditions, but it may not be robust enough to handle disturbances and uncertainties in the system. This can lead to poor performance or instability in practice;

- requirement for linearization: The LQR controller design requires the system to be linearized around an operating point, which may not be feasible for highly nonlinear systems.

To address these limitations, future research could focus on developing more accurate models for nonlinear systems, exploring more efficient optimization algorithms for controller design, and investigating the robustness of controllers to disturbances and uncertainties. Additionally, alternative control methods such as nonlinear control and adaptive control could be explored as potential solutions to overcome the limitations of LQR controller design.

7. Conclusions

1. The proposed ABC-LQR controller was successfully built to stabilize inverted pendulum systems.

2. A comparison with a conventional LQR controller was made in this paper to highlight the benefits of the presented approach.

3. The results showed that the proposed controller can handle the angles rotation (1, and 2) of the inverted pendulum and the linearized system cart position. The proposed ABC-LQR controller is a promising solution for stabilizing nonlinear DIP systems. The ABC algorithm used in the controller design provides an effective means of optimizing the LQR controller gains, which can lead to improved performance and stability of the system. However, it is important to consider the limitations of the approach, such as model inaccuracies, computational complexity, and sensitivity to disturbances. These limitations should be taken into account when applying the controller in practice, and further research is needed to develop more accurate models, explore more efficient optimization algorithms, and investigate the robustness of the controller. Overall, the proposed ABC-LQR controller represents an important contribution to the field of control engineering and has the potential to be a valuable tool for stabilizing nonlinear DIP systems in a range of applications.

4. Simulation findings reveal that employing artificial intelligence (AI) together with the proposed LQR controller outperforms by more than 50 % in transient response compared to the conventional LQR controller, and thus, can open new directions to improve performance characteristics for modeling control systems.

Hence, the proposed ABC-LQR approach can be used to achieve stability at a reduced time response.

Conflict of interest

The authors of this work (Mohammad A. Thanoon, Sohaib R. Awad, Ismael Kh. Abdullah) declare that they have no conflict of interest in relation to this research.

Financing

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Data availability

The manuscript has no associated data.

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The study is devoted to the expander turbine rotation speed regulator, considering the possibility of implementing this regulator on microprocessor automation tools. The use of expander-generator units in general improves energy saving indicators, and the ability to maintain the turbine shaft rotation speed within the specified limits, in turn, directly affects the indicators of the quality of the generated electricity. The expander turbine, as a control object, is described by non-linear equations, which determines the possibility of using regulators of different designs, and requires the selection of the most suitable one according to certain criteria. As part of the study, based on the tasks of practical implementation of the regulator on microprocessor devices, the expediency of reducing the transfer function of the model in the process of identifying the control object was confirmed. As a result of research on an experimental setup, it is shown that the use of a three-position relay regulator allows for regulation dynamics at the level of a classic PID regulator. An important result of the research is the stabilization of the turbine rotation speed, which affects the parameters of the electricity generated by the generator. The description of the control object was linearized by constructing a family of transfer functions for the operating points of the control range. For the construction of the turbine rotation speed regulator, the criterion of "minimum fluctuation of the parameter when changing its set value" is proposed. A regulator for a non-linear object with oscillatory features is built, which has a simple implementation and a cycle time of 1 ms. It makes it possible to reduce rotation speed fluctuations to 5 % and minimize the impact of rotation process disturbances

Keywords: nonlinear plant, adaptive control, relay regulator, plant model, reduced model

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DEVELOPMENT OF THE METHOD OF CONSTRUCTING THE EXPANDER TURBINE ROTATION SPEED REGULATOR

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1. Introduction

One of the ways to increase energy saving indicators in the transportation of natural gas is the use of expander-generator units (EGU). Electricity generated due to the use of excess gas pressure can be consumed both autonomously and by the network of users. In any case, the quality indicators of the generated electricity depend on the stability of the expander turbine, which rotates under conditions of changing gas flow parameters.

Solving the tasks of controlling turbine rotation modes is relevant for the small power industry – mini hydroelectric power plants (HPP) and wind energy devices. The need for control is due to the arbitrary nature of flow disturbances interacting with the turbine blades. Each of the streams has its own flow characteristics, which are considered when developing models and regulators of the control object.

Features of the description of such control objects consist of nonlinear equations, which are basic for the development of regulators of hydro- and aerodynamic processes param-

eters. Traditionally, approaches to the synthesis of regulators are based on the linearization of models, which allows the use of proven methods and algorithms during synthesis. However, at the stage of implementing the regulator at the facility, certain resources are spent, with the help of which the errors and stability of the regulation are evaluated or the regulator is adjusted at individual operating points of the operating range.

An alternative to the use of classic PID controllers used in linearized systems are fuzzy and neurocontrollers. The advantages of using the latter are manifested in cases when the object model is quite complex or its development is problematic. An additional convenience of using nonlinear regulators opens up when they are implemented in discrete computers in accordance with formalized criteria.

At the same time, neurocontrollers can realize their advantages (adaptability, robustness) only if they are adequately trained. At the same time, the process of "training" such a regulator usually requires no less resources than those spent on developing an accurate model. This refers to a num-