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OPTIMAL LQR CONTROL OF A PENDULUM BASED OVERHEAD CRANE USING THE WHALE OPTIMIZATION ALGORITHM

Research paper

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Abstract: This study represents an optimal LQR control approach to controlling the trolley movement of an overhead crane and sway reduction of its payload. The aim of the study is to improve the crane's positioning accuracy and ensure smoother and safer operations with less swinging motion of payload. To achieve this, a Linear Quadratic Regulator (LQR) controller is proposed, which generates optimal control signal as input force. However, instead of manually tuning the LQR gains, The Whale Optimization Algorithm (WOA), a nature-inspired method that mimics the hunting behavior of whales, is used to tune control parameters. The results show that this LQR-WOA combination effectively improves the system's stability, reducing oscillations efficiently and precisely the position of trolley. This approach offers a practical solution for industries where precise and safe overhead crane operation is essential.
Key words: Whale Optimization Algorithm, Linear Quadratic Regulator, overhead crane.

INTRODUCTION

Overhead cranes are important machines in industries which need heavy material handling and heavy loads by travelling along rails mounted on the ceiling. However, one of the biggest challenges in controlling overhead cranes is generating both precise positioning of the trolley and reducing the sway of the payload during movement. The dynamic behavior of this type of crane causes oscillatory movements of the payload, usually during the initial movements and sudden stops. If these oscillation movements are not controlled, it causes safety risks for equipment and personnel. In order to solve these kinds of issues, designing an effective control strategy is essential. Various controllers have been proposed to control overhead crane position and sway reduction in the literature such as proportional integral derivative, sliding mode, fuzzy logic and input shaping controllers [1-5]. Moreover, LQR controllers are also proposed to control these kinds of systems [6]. Additionally, in the literature, various optimization algorithms are used to obtain controller parameters of overhead cranes [7-9]. In the author's previous work, optimization of LQR controller using the Genetic Algorithm (GA) is proposed [10]. In this paper, the results obtained using the Whale Optimization Algorithm (WOA) for tuning LQR control gains are compared with the previous GA-based approach, highlighting the performance differences in terms of crane trolley positioning, sway reduction and applied control force.

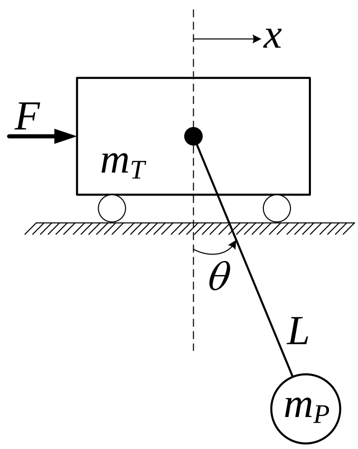

Fig. 1. *Single pendulum based overhead crane.*

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MATERIAL AND METHODS

Mathematical Modeling

In this section, mathematical modeling of a pendulum based overhead crane is presented. The mathematical modeling of an overhead crane system basically represents it as a combination of a cart (crane's trolley) and a pendulum (payload), which can be modeled as a pendulum [5]. When deriving the mathematical model of overhead cranes, the system can be represented as either a single pendulum or double pendulum configuration. In this study, focused on the single pendulum based overhead crane, as shown in Fig. 1. In this figure, x, θ and F represent the horizontal position of the trolley (cart), angle of the pendulum (payload sway) and control force applied to the trolley, respectively. These parameters vary as a function of time.

The equations of motion (1) and (2) for a single pendulum based overhead crane describe how the trolley and the swinging payload move. These equations can be derived using Newton's laws or Lagrangian mechanics. The trolley's motion depends on the control force and the swinging of the payload, considering the masses of both. The pendulum's swing is influenced by gravity and the trolley's movement.

$$(m_T + m_P)\ddot{x} + m_P L cos\theta \ddot{\theta} - m_P L sin\theta \dot{\theta}^2 = F \quad (1)$$

$$m_P L cos\theta \ddot{x} + m_P L^2 \ddot{\theta} + m_P g L sin\theta = 0 \quad (2)$$

For small angles of the pendulum sway, the system is typically linearized using approximations $sin\theta \approx \theta$ and $cos\theta \approx 1$ This simplification makes the model easier to work with, especially for control design. To design LQR controller, it's required to represent the system in state-space form shown in equation (3). The state variables and output variables can be defined as in equation (4).

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \quad (3)$$

$$x^T = [x \quad \dot{x} \quad \theta \quad \dot{\theta}] , y^T = [x \quad \theta] \quad (4)$$

In state-space form, A is the system matrix, B is the input matrix, C is the output matrix and D is the direct transmission matrix. For the pendulum based overhead crane, these matrices are defined and given in (5).

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{m_T g}{m_P} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\frac{(m_T + m_P) g}{m_P L} & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{1}{m_P} \\ 0 \\ -\frac{1}{m_P L} \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (5)$$

For the purpose of simulating the system, the system parameters used in the model are presented in Table 1. These parameters are selected based on the author's previous work to enable a direct comparison of the results between two different optimization methods.

Table 1. *Overhead crane system parameters*

The Parameters	m_T	m_P	L	g
Value	3.9 kg	1 kg	0.3 m	9.81 m/s^2

The Whale Optimization Algorithm (WOA)

Optimization algorithms are widely used to find the best solution for a problem by either minimizing or maximizing an objective function. This is an important significance in engineering, these algorithms help improve the control systems' performance and stability. In this paper, The Whale Optimization Algorithm (WOA) is used, a popular method inspired by the hunting behavior of humpback whales [11]. By mimicking their spiral movements that are constantly narrowing by releasing bubbles which are only seen in humpback whales shown in Fig. 2. WOA efficiently searches for optimal solutions in complex problems. The hunting strategy of humpback whales consists of three basic stages; coral loop, forming a circle around the prey (the best solution) by releasing air bubbles, lobtail; then narrowing the circle and approaching the prey with a spiral movement and capture loop; searching for prey.

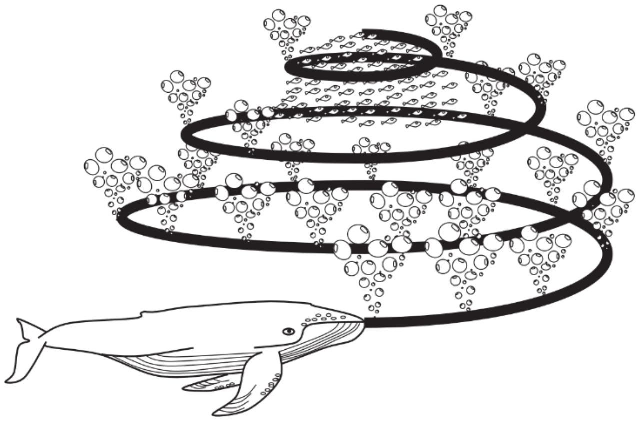

Fig. 2. *Hunting behavior of humpback whales [11].*

In control systems like LQR controllers proposed in this paper, selecting the right control gains is essential but often difficult. Optimization algorithms simplify this by automating the process of finding the optimal gains, obtain to better system performance via selected objective function. In this paper Q and R matrices of the Linear Quadratic Regulator (LQR) is optimized for obtaining the optimal state feedback gain matrix K, as explained in following section.

Optimization of Linear Quadratic Regulator (LQR)

In an overhead crane system, controlling the trolley position while reduction the sway angle of the payload is an important process for smooth operation and safety. The Linear Quadratic Regulator (LQR) is an optimal control technique that can effectively handle this problem by minimizing both the error in trolley position and the swing of the payload [10]. It is also minimizing the control signal which applied force to the trolley in this study. The main goal of LQR is to minimize a cost function, which typically combines state and control input penalties. The cost function is generally of the form shown in equation (6).

$$J = \int_0^\infty (x^T Q x + u^T R u) dt \tag{6}$$

By selecting appropriate Q and R matrices shown in previous equation, based on the desired trade-offs between state error and control effort, the optimal control input u is derived from the state feedback law shown in equation (7). In this equation, K is the gain matrix derived by solving the Riccati equation. Moreover, LQR need A and B matrices defined in systems state-space representation.

$$u = -Kx \tag{7}$$

In this study, The Whale Optimization Algorithm (WOA) is utilized to obtain the optimal Q and R matrices. Once these optimal matrices are determined, they are used to compute the gain matrix K which is then implemented in simulations to obtain results. All simulations are conducted on the MATLAB platform using both the MATLAB programming language and Simulink, a block diagram environment used to design systems, on a system equipped with an Intel(R) Xeon(R) CPU E5-1620 v2 @ 3.70GHz and 16 GB of RAM. The block diagram of the control system, created using MATLAB Simulink, is shown in Fig. 3.

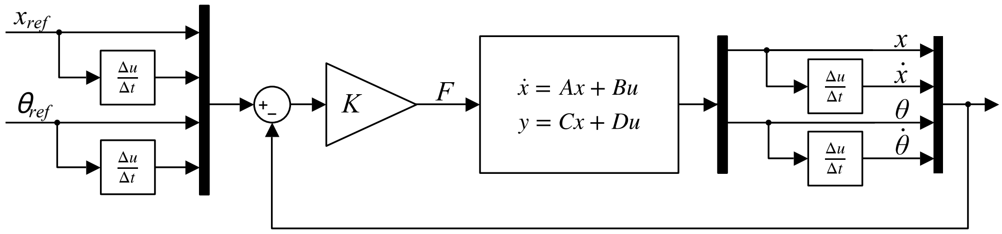

Fig. 3. *LQR Control block diagram of overhead crane system.*

30 search agents and a maximum number of 30 iterations are utilized to solve the proposed problem. The objective function of this study is given in equation (8). The objective function includes the parameters of rise time, settling time, peak time, maximum peak and steady state error which are obtained from the trolley position and sway angle results during the optimization process. To achieve the best results, specific ranges of values are chosen for use in the optimization process. The selected ranges for optimization are presented in Table 3.

$$J = (x_{tr} + x_{ts} + x_{tp} + x_{max} + x_{sse}) + (\theta_{norm} + \theta_{ts} + \theta_{tp} + \theta_{max} + \theta_{sse}) \quad (8)$$

Table 3. *Ranges of the optimization parameters.*

	Q_{11}	Q_{22}	Q_{33}	Q_{44}	R
Min	0	0	0	0	0
Max	200	100	200	100	2

Optimal Q and R matrices are obtained shown in equations (9). The gain matrix K is derived shown in equation (10) by optimal Q and R matrices.

$$Q = \begin{bmatrix} 199.6957 & 0 & 0 & 0 \\ 0 & 47.1646 & 0 & 0 \\ 0 & 0 & 11.6723 & 0 \\ 0 & 0 & 0 & 35.4262 \end{bmatrix}, R = 0.1037 \quad (9)$$

$$K = [43.8837 \quad 37.8594 \quad -61.3007 \quad -9.3122] \quad (10)$$

Minimization of the objective function (J) shown in Fig. 4. which demonstrates that the number of iterations is sufficient to observe the results.

Fig. 4. *Minimization of the objective function (J).*

RESULTS AND DISCUSSION

The optimization of the Linear Quadratic Regulator (LQR) using the Whale Optimization Algorithm (WOA) is compared with the author's previous work. The results displayed in graphical form demonstrate the effectiveness of the selected Q and R matrices. Simulation outcomes reveal that the optimized gain matrix K significantly reduces both overshoot of the trolley position and oscillation of the payload, thereby minimizing the sway angle in Fig. 5. and Fig. 6. respectively.

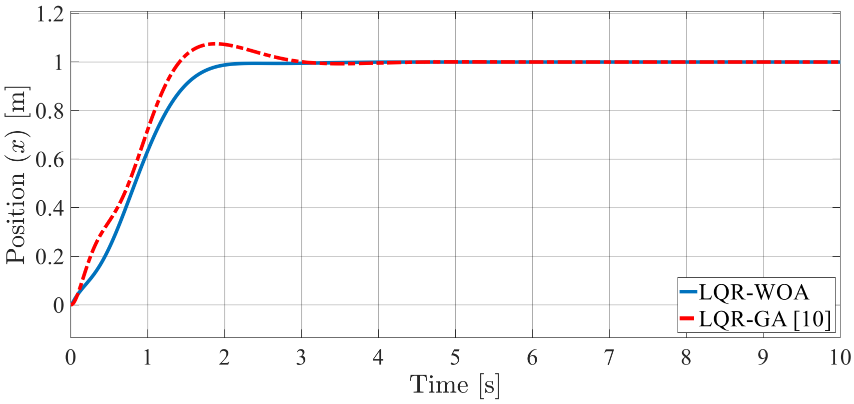

Fig. 5. *Trolley position results of the overhead crane*

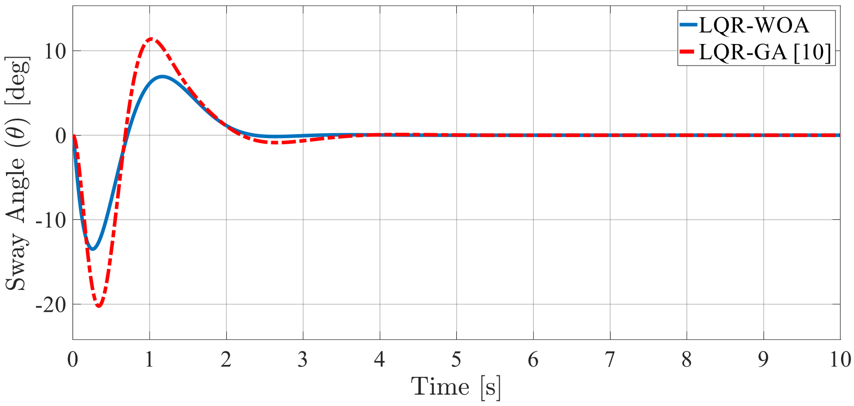

Fig. 6. *Sway angle results of the overhead crane*

The control force applied to the trolley, as determined by the optimization process shown in Fig. 7. presents a reduction in the overall force applied to the trolley. This means WOA optimized LQR control applies less force to achieve the desired motion.

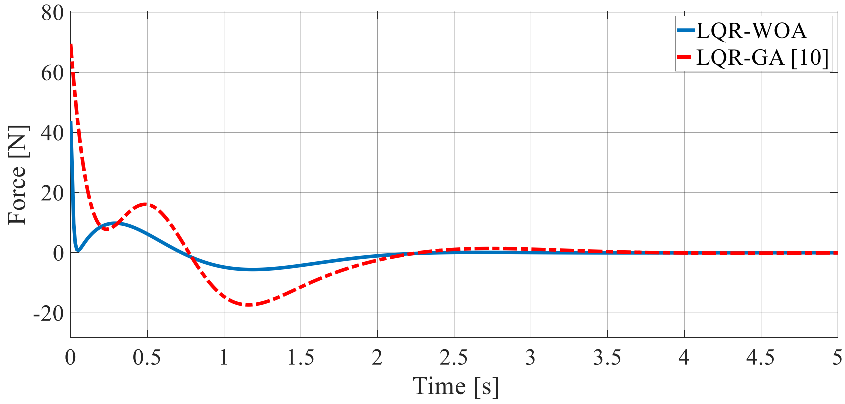

Fig. 7. *Input force results applied by LQR controller*

CONCLUSION

In this study, the LQR (Linear Quadratic Regulator) control strategy for an overhead crane was optimized using the Whale Optimization Algorithm (WOA). By tuning the Q and R matrices optimally, it is demonstrated how WOA effectively minimizes the cost function, enhancing the performance of overhead crane systems, ensuring safer and more effective operations in various industrial applications. And it can be said that it provided energy efficiency in this case because the system requires less force. The resulting optimal gain matrix K ensures precise positioning of the trolley while significantly reducing payload sway. These enhancements underscore the successful implementation of the LQR controller and highlight the potential of integrating WOA with LQR for optimal control applications, marking an improvement over prior result. Overall, the integration of optimization algorithms with control methods provides a robust and efficient solution for enhancing the performance of control systems.

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