Position control to expand the headlights' angle of a car by DC motor drive system using PSO algorithm for speed loop

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ABSTRACT

Today, along with the robust development of society, cars are almost considered a primary means of transportation. This article focuses on designing headlight controls for older car models that are not equipped with adaptive headlight systems (AHS), which are different from modern cars such as Porsche, BMW, Audi, and Mercedes-Benz vehicles. The design is for a lighting system that operates during nighttime to improve illumination and enhance visibility in curves, with cost-effective and suitable solutions for average vehicles to ensure safety. This system uses a DC motor to control the headlight angle based on the steering wheel rotation. It is combined with the particle swarm optimization (PSO) algorithm to find the best response parameters for the proportional-integral-derivative (PID) controller. Research results on the MATLAB/Simulink and the experimental model show that the model established by this method has good accuracy, the controllers can significantly reduce the excessive deviation of the headlights' operational precision, and traffic accidents can be minimized, increasing safety for users.

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1. INTRODUCTION

Nighttime traffic accidents have become increasingly common, with rates two to three times higher than during the day, primarily involving standard car models and particularly older vehicles [1]. A pressing issue is that these standard car models are still widely used for transportation and movement [2]. The cause of these accidents is that these older models still use traditional headlights without adaptive lighting systems, leading to impaired driver visibility when making turns or driving over hills [3]. Traditional headlights consist of several lamps with simple optics designed to direct the light beam onto the road [4]. Recognising the limitations of conventional headlights, adaptive lighting systems have been developed to adjust the brightness to accommodate changing driving conditions [5]. The state of the driver, terrain conditions, and weather also contribute to safety risks [6].

The primary function of headlights is to illuminate the road for the driver [7]. They create a typical signalling aspect to identify the vehicle for upcoming traffic. Moreover, they must avoid blinding other road users with glare. Previously, headlights were almost a static system. They only provided two capabilities to modify light distribution- low and high. The development goal of modern headlights is a highly dynamic system capable of adapting to numerous events. Studies have also been aimed at addressing the issues for these average car models, but the effectiveness has not been high partly because they have not yet met the conditions of users in terms of cost and convenience [8].

In this article, we present a cost-effective method to address the existing issues of lighting systems, such as the visibility range of headlights and minimising accidents. In this study, we have used a new and beneficial method to adjust the lighting angle of the headlights for different road conditions and vehicle speeds based on steering control [9]–[13]. This method allows drivers to observe a broader range and reduces traffic accidents due to insufficient headlight lighting. The results of this study will help develop a more efficient headlight system that can be implemented in various types of vehicles.

A practical method employed in this study is the particle swarm optimisation (PSO) technique to find the parameters for the motor controller with high reliability and accuracy [14]–[16]. Combining a DC motor and PSO delivers superior effectiveness in light adjustment, which marks a significant advancement in the modern automotive industry. With its ability to adapt instantly and accurately, the adaptive headlight system using PSO [17] has opened a new chapter in the era of automotive lighting, moving towards a future where technology and safety go hand in hand. Finally, the validity and correctness of the proposed methods will be demonstrated through simulations using MATLAB/Simulink and practical results [18].

2. MODELING THE ACTUATION SYSTEM FOR HEADLIGHTS

Adaptive headlights are not new to some modern, expensive car models. However, some budget constraints have prevented full implementation for more affordable car brands. Figure 1 shows the schematic structure of the system controlling the headlight angle based on the steering angle and the tilt angle of the car. Input signal block includes the steering wheel's steering and the car's tilt angles; central processing unit: controllers receive input and control output signals; output signal block: the optimal headlight angle values for movement. The solution here aims to control the extension of the headlight beam when the car moves into challenging terrain, enhancing visibility around corners. The DC motor controls the expanded lighting area when the car moves at night, and an H-bridge circuit reverses the motor's direction.

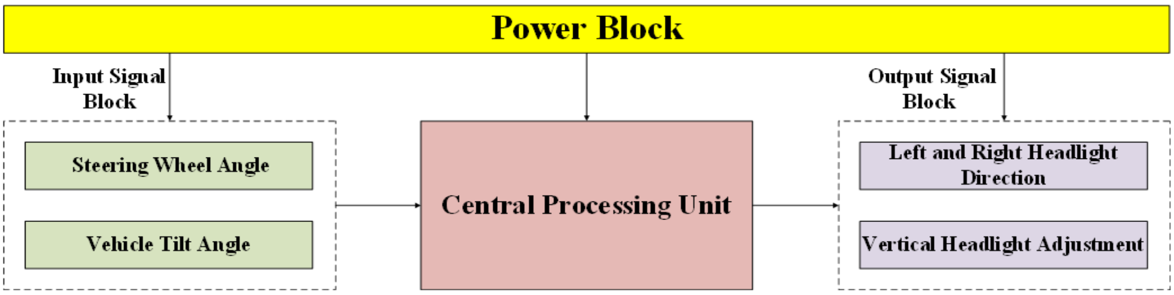


Figure 1. Block diagram of the adaptive headlight control system

2.1. Modeling DC motor

The equations typically describe the voltage balance in both the armature and the field coil, along with the mechanical dynamics related to torque, speed, and inertia of the DC motor [19], which are given by (1):

$$\begin{cases} u_A(t) = e_A(t) + R_A i_A(t) + L_A \frac{di_A(t)}{dt} \\ M_m = \frac{pN}{2\pi a}\phi I_A = k_M \phi I_A \\ e_A(t) = K_e \omega(t) \\ M_m - M_c = J\frac{d\omega}{dt} \end{cases} \tag{1}$$

Where U_A is the induced voltage, R_A is the resistance of the inductor, L_A is the inductance of the inductor, I_A is the current through the inductor, E_A is the electromotive force of the inductor, M_m is the motor torque, M_c is the opposing torque, J is the moment of inertia of the motor, K_M is the torque constant, and ω is the angular speed.

3. DESIGNING POSITION CONTROL OF HEADLIGHTS

The drive control structure to rotate the angle of headlights includes three loops: current, speed, and position. Among three loops, the PI controller combined with the PSO [20] algorithm in the speed loop, using an H-bridge circuit to control the DC motor for the headlight's right and left tilt, as presented in Figure 2.

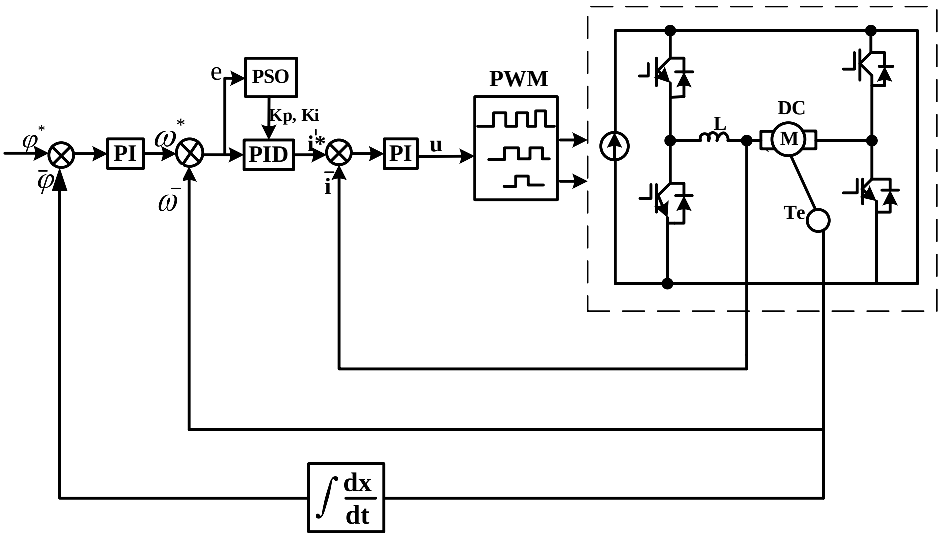


Figure 2. DC motor control structure diagram

3.1. Current loop synthesis

In a DC drive system, the current loop is a fundamental circuit determining the motor's torque [21]. We assume that the system has a mechanical time constant greater than the electromagnetic time constant of the inductor circuit [22], [23]. Therefore, in this case, the influence of the induced electromotive force can be neglected. The motor's current control loop structure is constructed as shown in the Figure 3.

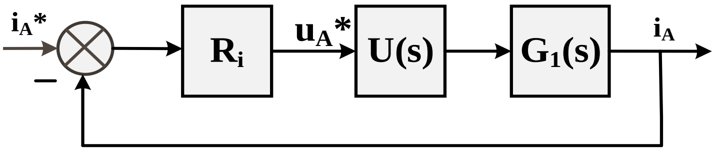


Figure 3. Circuit loop diagram

From the first (1), when transformed into the Laplace domain, we obtain:

$$U_A(s) = E_A(s) + R_A I_A(s) + L_A s I_A(s) \tag{2}$$

With $U(s) = \frac{1}{1+T_t s}$ is a rectifier stage, we have the transfer function of the reactive circuit:

$$G_i(s) = \frac{i_A(s)}{u*_A(s)} = \frac{1}{R_A} . \frac{1}{1+T_t s} . \frac{1}{1+sT_A} \tag{3}$$

The transfer function of the object in the current loop circuit is a second-order inertial link. We choose a PI controller designed according to the optimal magnitude criterion. The proportional-integral (PI) controller has the form: $R_i = k_p(1 + \frac{1}{sT_I})$.

By applying the magnitude optimisation method, we obtain the transfer function of the open-loop system.

$$G_h(s) = G_i(s).R_i(s) = \frac{1}{R_A}\frac{1}{1+T_t s}\frac{1}{1+sT_A}k_p(1+\frac{1}{sT_I}) \quad (4)$$

To implement the compensation for the time constant T_A, select $T_A = T_I$, and from there, we obtain the transfer function of the open-loop system:

$$G_h(s) = \frac{k_P}{R_A}.\frac{1}{1+T_t s}.\frac{1}{sT_I} \quad (5)$$

We have:

$$G_k(s) = \frac{G_h(s)}{1+G_h(s)} => |G_k(j\omega)| = \frac{\frac{1}{R_A}}{\sqrt{\left(\frac{1}{R_A}-\frac{T_I}{k_P}.T_t\omega^2\right)^2+\left(\omega.\frac{T_I}{k_P}\right)^2}} \quad (6)$$

To ensure that the formula $|G_k(j\omega)| = 1$ operates within a low-frequency range with a large bandwidth, one can choose: $\left(\frac{T_I}{k_P}\right)^2 - 2\frac{1}{R_A}\frac{T_I}{k_P}T_t = 0$. From this, we can obtain:

$$\frac{T_I}{k_P} = 2\frac{1}{R_A}T_t => k_P = \frac{T_I}{2\frac{1}{R_A}T_t} = \frac{T_A}{2\frac{1}{R_A}T_t} => k_i = \frac{k_p}{T_I} = \frac{k_p}{T_A} \quad (7)$$

3.2. Using the particle swarm optimization algorithm to find the parameters of the speed loop controller

The PSO algorithm is a stochastic optimisation technique based on a population of multiple individuals to find the optimal solution by updating generations [24]. In the PSO algorithm, each swarm member is characterised by current position and velocity. Each individual generates a position according to its velocity, remembers its previous position, and compares it to the best position previously generated by others according to the objective function. An element constantly searches within its own search space to replace the old position with the best new [25].

In each iteration, the velocity and position of each individual are adjusted based on the following relationship:

$$\begin{cases} V_i(k+1) = J(k)V_i(k) + c_1\left(P_{best,i}(k) - X_i(k)\right)R_1 + c_2\left(G_{best,i}(k) - X_i(k)\right)R_2 \\ X_i(k+1) = X_i(k) + V_i(k+1) \end{cases} \quad (8)$$

With *J(k)* representing the inertia coefficient for each iteration, $J(k) = w + rand$, *rand* generates a random number within the range [0, 1]; c_1 and c_2 are called the cognitive and social coefficients, respectively, and typically range from $0<c_1,c_2<4$; the two matrices R_1 and R_2 are diagonal matrices (or variables uniformly distributed) consisting of random numbers in the range [0, 1].

When the speed reaches a nominal value, the voltage will reach the voltage U_{sm}. Therefore, to increase the speed further, it needs to reduce the flux ψ, which also means reducing torque. This is shown in Figure 4. To find the K_P and K_I coefficients of the PI controller, use the objective function formula to search for the best individuals based on the minor error using the PSO algorithm, as in Figure 5.

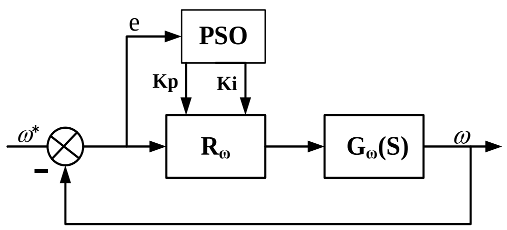


Figure 4. Velocity loop circuit diagram incorporating PSO algorithm

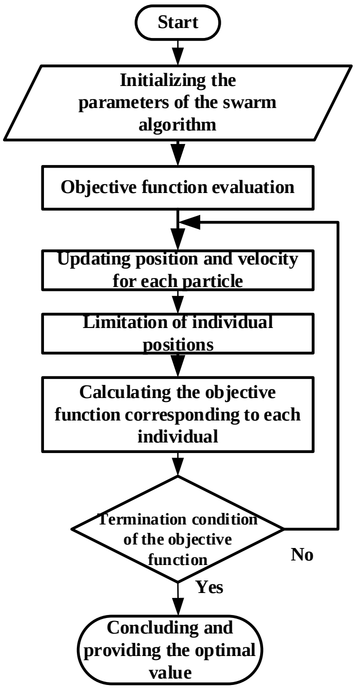


Figure 5. PSO algorithm diagram

3.3. Synthesis of the position loop

After designing the speed control loop for an approximate design, we consider the transfer function of the speed control loop as a first-order function:

$$F_\omega(s) = \frac{k_\omega}{1+T_\omega S} \tag{9}$$

In this case, K is the amplification factor and the time constant of the closed-loop speed circuit. Figure 6 shows the control structure of the position control loop.

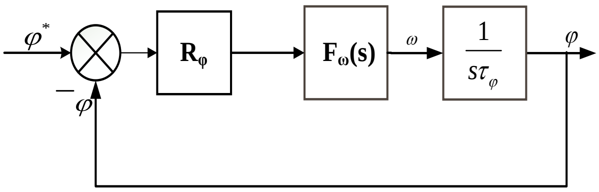


Figure 6. Position loop circuit diagram

We observe that the controlled object is a first-order integral-inertial element, so we choose a PD controller to adjust according to the symmetric optimal tuning principle:

$$R_\varphi(s) = k_P\left(1+\frac{1}{sT_I}\right) \tag{10}$$

We have the open-loop transfer function:

$$F_h(s) = R_\varphi.F_\omega = k_P\left(1+\frac{1}{sT_D}\right).\frac{1}{s\tau_\varphi}.\frac{k_\omega}{1+T_\omega S} \tag{11}$$

We draw the Bode plot of G(s) with ‘a’ being the distance between two corner frequencies ω_1 and ω_2, and the cutoff frequency ω_c lying between the two frequencies: $\omega_1 = \frac{1}{T_I}$, $\omega_2 = \frac{1}{T_\omega}$, $\omega_c = \frac{1}{\sqrt{2T_\omega T_I}}$. The parameters of the PI controller are calculated and chosen with a=4. $lga = lg\omega_2 - lg\omega_1 = lg\frac{T_I}{2T_t} => T_I = 8T_\omega$,$|F_h(j\omega)| = 1 => k_P = \frac{J}{k_m 2T_r\sqrt{a}} = \frac{J}{4.T_t}$,$k_i = \frac{k_p}{T_I}$.

4. SIMULATION AND PRACTICAL RESULTS

The steering wheel rotates from the 0° position to the right by 210° (3.66 rad/s), causing the headlight to shift to the right by 20° (0.349 rad/s). The steering wheel rotates from the 0° position to the left by 210° (3.66 rad/s), causing the headlight to shift to the left by 20° (0.349 rad/s). The simulation parameters are presented in two tables. Table 1 presents the DC motor parameters in a certain electric car, while Table 2 presents the parameters of the electric vehicle and the environment. Table 3 shows the parameters of the PI controller and the parameters of PI combined with PSO.

Table 1. The parameters of the DC motor

Parameters	Value
Rated voltage, U	12 V
Rated power, P	10 W
Rated current, I	0.8 A
Reactive impedance, R_A	2 ohm
Reactive inductance, L_A	0.01 H
Rated speed, n	2,500 rpm
Inertia moment, J	0.0002 kg.m^2

Table 2. The parameters of PSO

Parameters	Value
Number of individuals in the population	20
Number of iterations	50
Inertial weight	0.9
Experience coefficient	2
Social relationship coefficient	2

Table 3. The parameters of PSO

Parameters	PI	PI-PSO
K_P	6.025	9.221
K_I	8.532	17.113
K_{P1}	28.551	28.551
K_{I1}	40.656	40.656

Figure 7 illustrates the position response of a DC motor using the PSO algorithm. The figure shows that the response value closely follows the initial set value, with the deviation between the two values being approximately zero. This result demonstrates that the PSO algorithm achieves a rapid and effective response. This assists in accurately and efficiently controlling the angle of the headlights to the desired position. The convergence of the search results using the swarm algorithm is shown in Figure 8. It demonstrates that the search coefficients are optimised after several iterations based on the objective function. After several iterations, the PSO algorithm accurately determined the K_p and K_i parameters of the PI controller, highlighting the differences between this method and traditional controllers, as shown in Figure 9.

Figure 9(a) shows the PI controller’s speed response, and Figure 9(b) uses the PSO algorithm. In Figure 9(a), the PI controller’s speed response shows that the actual signal did not closely follow the setpoint and had a sizeable steady-state error. Meanwhile, Figure 9(b) demonstrates that the feedback signal closely tracked the setpoint.

From this, it can be said that the PSO algorithm method turning K_p, K_i has a better response than the conventional PI control; the speed error is almost zero. This assists in accurately controlling the headlight angle to the desired position, improving the illumination angle, and increasing the beam spread.

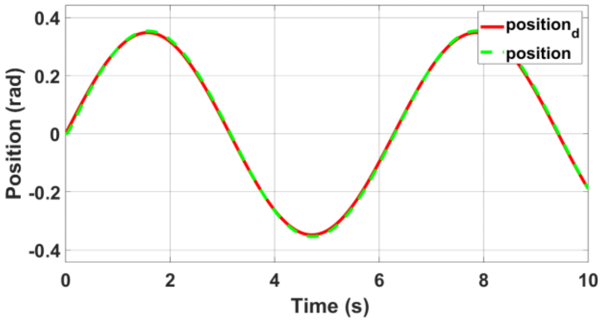


Figure 7. Position response of a DC motor

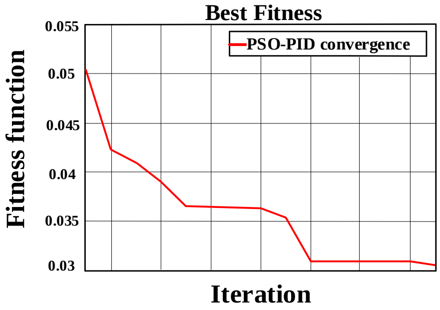
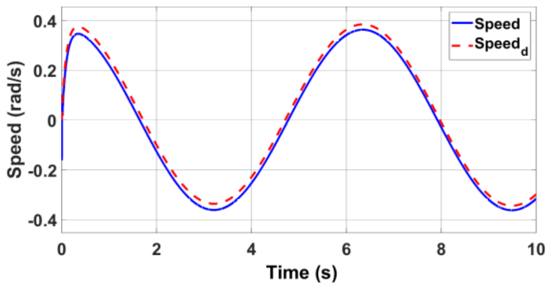
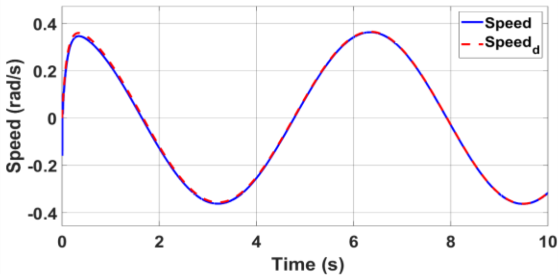


Figure 8. Convergence of PID coefficient search using PSO



(a)

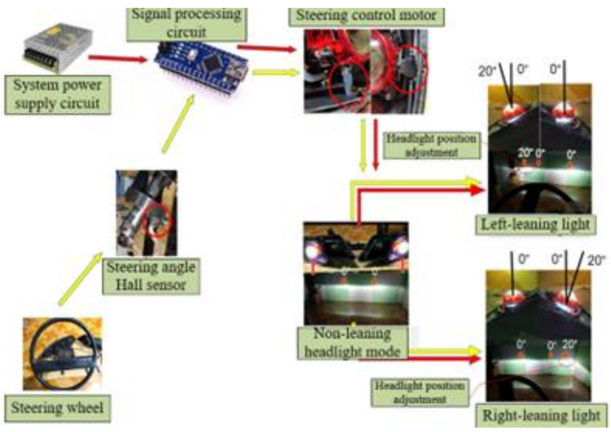


(b)

Figure 9. The speed responses; (a) the speed response of PI controller and (b) the speed response of the PSO algorithm

The study's results are demonstrated through experiments in Figure 10(a), using a spherical bulb, a DC motor, and sensors such as a fixed Hall sensor on the casing. It reads the changing angles of the steering wheel rim, and then the signal is sent to an Arduino processing circuit to determine the steering wheel's rotation direction. The light angle is controlled based on the steering wheel angle, as demonstrated in Figure 10(b) shows that in the initial state, before controlling the light to turn left or right, the beams intersect at a specific position. Suppose we control the light to turn 20 degrees to the left and 20 degrees to the right. In that case, it still ensures the intersection point between the two lights while simultaneously expanding the beam angle, which enhances the viewing angle and helps reduce the risk for drivers driving at night.

(a)



(b)

Figure 10. Experimental model for adaptive lighting control in cars; (a) components of the experimental model and (b) results of the experimental model for adaptive lighting control

5. CONCLUSION

The simulation results using MATLAB/Simulink have demonstrated the significant effectiveness of the adaptive headlight system using a DC motor combined with the PSO swarm optimization algorithm. This reinforces the role of advanced technology in enhancing driving safety and is an essential step for future applications in the automotive industry. The adaptive headlight system aims to control and expand the effective light angle for drivers to enhance visibility during cornering based on the steering wheel angle. This system meets user needs for cost-effectiveness, simple and efficient assembly, and increased safety. Experimental results demonstrate improved illumination when driving at night. The article proposes a method to optimize the PID controller coefficients using the PSO algorithm applied to a DC motor. Additionally, it ensures the highest accuracy to reduce response time when meeting the steering wheel's requirements affecting the headlights. This enables precise and efficient headlight control based on steering input.

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