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DESIGN AND FABRICATION OF AN OPTIMAL CONTROLLER FOR A MOTOR IN A RADIO POSITIONING SYSTEM

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ABSTRACT

The paper presents the research outcomes of the project titled “Design and fabrication of an optimal controller for a motor in a radio positioning system” aimed at enhancing the stability and control quality of the antenna rotation angle in radio positioning systems by utilizing an LQR controller as a replacement for the traditional PID controller. The product serves research and educational purposes at the AD - AF Academy, and it has high applicability in practical operations, contributing to improved performance and reliability of radio positioning systems, especially in missions that require high precision and quick response.

Keywords: LQR, PID, DC servo motor.

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1. INTRODUCTION

AD - AF equipment is a modern asset currently being utilized by the Viet Nam. Among these, the radio positioning system is used to determine the position or relative location of an object through the use of radio waves. In traditional radio positioning systems, DC servo motors and PID controllers are commonly used. The limitations of traditional radio positioning systems include the inability of PID controllers to optimize control performance according to specific criteria, such as minimizing errors or optimizing energy consumption. The PID control method has limited stability and lacks flexibility when dealing with complex state-space variations or special control requirements [4].

LQR (Linear Quadratic Regulator) is an optimal control method used to design controllers for linear systems. The LQR controller has the advantage of optimizing control performance based on a specific cost function that optimizes system performance, achieving control objectives with minimal errors, and providing quick and flexible responses. The LQR controller is better at handling disturbances compared to the PID controller, which helps improve stability and control quality [9].

For these reasons, the research team proposes the project "Design and fabrication of an optimal controller for a motor in a radio positioning system." This project is essential to replace the PID controller with an optimal LQR controller for small-power DC servo motors in radio positioning systems.

2. OVERVIEW OF THE RADIO POSITIONING SYSTEM

A radio positioning system is an advanced technology that utilizes radio waves to accurately determine the spatial location of an object. This system is based on the fundamental principle of measuring the time delay that occurs as a radio signal travels from the transmitter to the target and then reflects to the receiver. By precisely calculating this time interval, the system can determine the distance to the target, and when integrated with other positional data, it can provide accurate information about the target's location in space [7].

The operating principle of a radio positioning system is twofold: first, it involves the transmission and reception of radio signals to detect and locate the target, and second, it requires the dynamic control of the antenna's orientation. The antenna must be continuously and accurately adjusted to maintain alignment with the target, ensuring optimal signal transmission and reception. This adjustment is crucial for maintaining the accuracy and reliability of the positioning system, particularly in scenarios where the target is moving or when high precision is required [5].

- Signal Transmission, Reception, Processing, and Display:

Signal transmission: The process begins with the transmitter, which generates a specific radio signal. This signal is then directed through a switching block, a component that manages the flow of the signal and is sent to the antenna unit. The antenna then broadcasts the signal into space, aiming it towards the target [6].

Signal reception: Upon encountering a target, such as an aircraft or a geographical feature, the radio signal is reflected back. This reflected signal is then captured by the receiving antenna, which is also connected through the switching block. The effectiveness of this reception depends on the precision of the antenna's alignment and the sensitivity of the receiver [6].

Processing and display: Once the reflected signal is received, it undergoes a series of processing steps. The received signal is fed into a processing and display unit, where sophisticated algorithms analyze the signal

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characteristics to extract valuable information. This includes determining the target's distance and direction. The processed data is then displayed on a screen, providing operators with real-time location information of the target, which can be used for various applications such as navigation, surveillance, or search and rescue operations.

- Antenna Rotation Control Process:

The control of the antenna's rotation is critical to the overall functioning of the radio positioning system. At the heart of this process is the PID controller, which plays a vital role in regulating the movement of the actuator motor responsible for rotating the antenna. The PID controller continuously monitors the antenna's position and makes precise adjustments to maintain the desired rotation angle. This ensures that the antenna remains accurately aligned with the target, allowing for optimal signal transmission and reception. The ability to maintain accurate and stable antenna positioning is crucial for the system’s efficiency, particularly in complex environments where signal clarity and reliability are paramount [6].

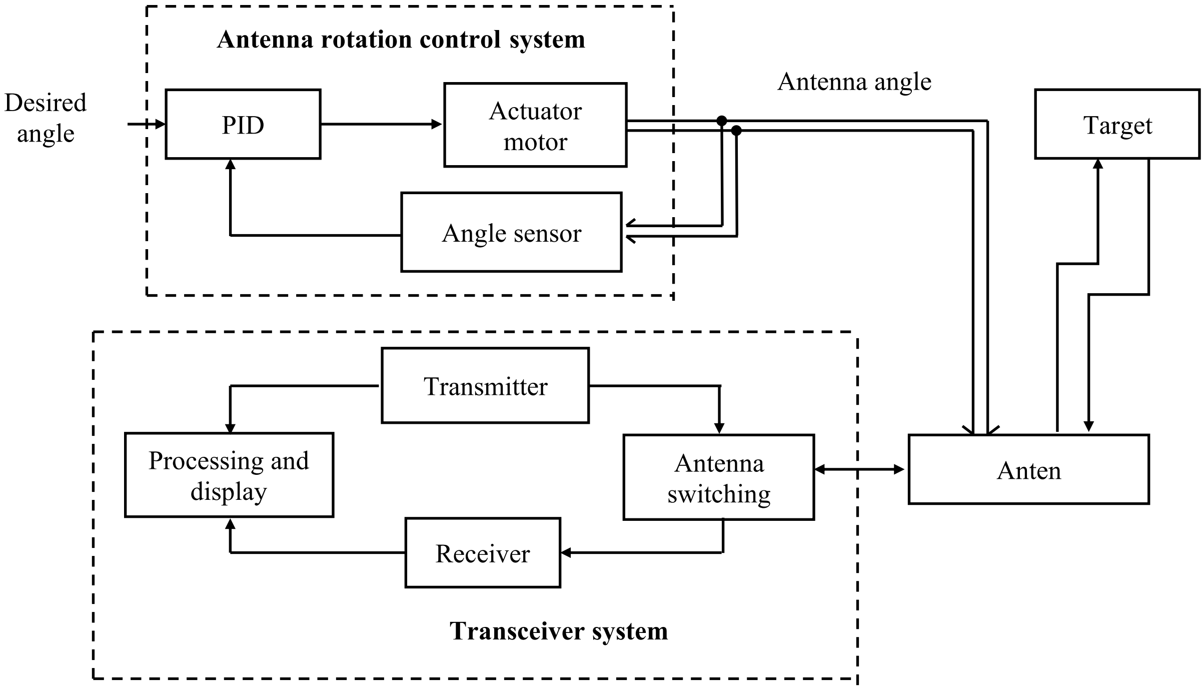

Figure-1. Block diagram of the radio positioning system.

3. MODELING THE ANTENNA ROTATION CONTROL SYSTEM USING A DC SERVO MOTOR AND LQR CONTROLLER

The antenna rotation control system is a control system designed to adjust and maintain the antenna's rotation angle to ensure it is always accurately aligned with the target or desired position. This system uses a DC servo motor, which plays a crucial role in applications such as communication, radar, and radio positioning systems, where high precision and efficiency are required for target alignment and tracking [1].

The antenna rotation control system employs the optimal state feedback control method, LQR (Linear Quadratic Regulator), allowing the system to operate with precision, stability, and efficiency in controlling the rotation angle of the DC servo motor that drives the antenna shaft. The author proposes replacing the traditional PID controller with an LQR controller, which is responsible for processing and optimizing control based on the input information and the current state of the system. The LQR controller will calculate the optimal control voltage (U) needed to be supplied to the DC servo motor to achieve the desired rotation angle [2].

The steps for synthesizing an LQR controller are as follows:

Step 1: Based on the equivalent circuit diagram of the DC servo motor, determine the mathematical model of the control object in the form of state-space equations.

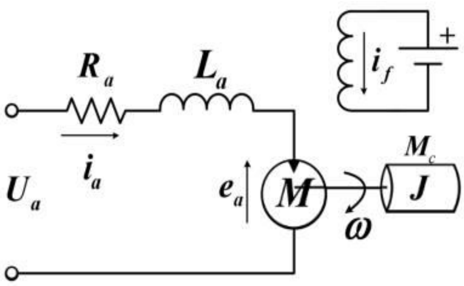

Figure-2. Equivalent circuit diagram of the DC servo motor.

Moment Balance Equation:

$$J.\frac{d\omega}{dt} = \tau \quad (1)$$

Where:
J - is the moment of inertia of the rotor (kg·m²)
ω - is the angular velocity of the rotor (rad/s)
τ - is the output torque (N·m)

The relationship between the output torque τ and the current ia is:

$$\tau = K_m.i_a \quad (2)$$

$$J.\frac{d\omega}{dt} = K_m.i_a \quad (3)$$

K_m is the torque constant (N·m/A).

The electrical balance equation is established according to Kirchhoff's second law:

$$L_a.\frac{di_a}{dt} + R_a.i_a + K_e.\omega = u_a \quad (4)$$

The equation relating to the angular position is:

$$\frac{d\theta}{dt} = \omega \quad (5)$$

In which:
θ is the angular position of the motor shaft (rad).
Let $x_1 = \theta$, $x_2 = \omega$, $x_3 = i_a$.

We have the following system of equations:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{K_m}{J}\cdot x_3 \\ \dot{x}_3 = -\frac{K_e}{J}\cdot x_2 - \frac{R_a}{L_a}\cdot x_3 + \frac{u_a}{L_a} \end{cases} \quad (6)$$

Choose the state variables as follows:

$$X = [x_1 \quad x_2 \quad x_3] \quad (7)$$

Output: Y = θ; Control input: $U = u_a$

The state-space equations are given by:

$$\begin{cases} \dot{X} = A.X + B.U \\ Y = C.X \end{cases} \quad (8)$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{K_m}{J} \\ 0 & \frac{-K_e}{L_a} & \frac{-R_a}{L_a} \end{bmatrix}; \; B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_a} \end{bmatrix}$$

$$C = [1 \quad 0 \quad 0]$$

La is the inductance of the stator winding (H).
R_a is the resistance of the stator winding (Ω).
u_a is the input voltage (V).
J is the moment of inertia of the rotor (kg.m²)

Step 2: The required performance criteria for the control system are as follows:

Steady-state error:	2%
Rise time:	2 seconds
Maximum overshoot:	10%
Setting time:	5 seconds

Step 3: Choose the control law as U = − K·X. In Matlab, the function K = lqr(A, B, Q, R) can be used to compute the feedback matrix K for the LQR controller.

For the requirement of controlling the system based on the angle, we select the weighting matrices Q and R as follows:

Weighting matrix Q: This matrix penalizes deviations in the state variables. It typically has diagonal elements that represent the importance of each state variable in the control performance. For controlling the angle, you might want to emphasize the position and velocity of the motor shaft. Therefore, Q can be set as:

$$Q = \begin{bmatrix} 150 & 0 & 0 \\ 0 & 15 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Weighting matrix R: This matrix penalizes the use of the control input. It is usually a scalar if there is a single control input. For instance: R = 1.

Step 4: Check the stability and evaluate the performance of the control system. Compare the performance of the system using the proposed LQR controller with the initial PID controller, as illustrated in Figure-3. The evaluation should be based on the required performance criteria and the step response of the system using each controller, as follows:

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Table-1. Quality of the control system using PID controller.

Parameter	Obtained criteria	Required criteria	Evaluate quality
Steady-state error (%)	0	2	Achieved
Rise time (s)	0.6767	2	Achieved
Maximum overshoot (%)	13.99	10	Not achieved
Transition time (s)	5.7433	5	Not achieved

Table-2. Quality of the control system using LQR controller.

Parameter	Obtained criteria	Required criteria	Evaluate quality
Steady-state error (%)	0	2	Achieved
Rise time (s)	0.6996	2	Achieved
Maximum overshoot (%)	0	10	Achieved
Transition time (s)	1.2464	5	Achieved

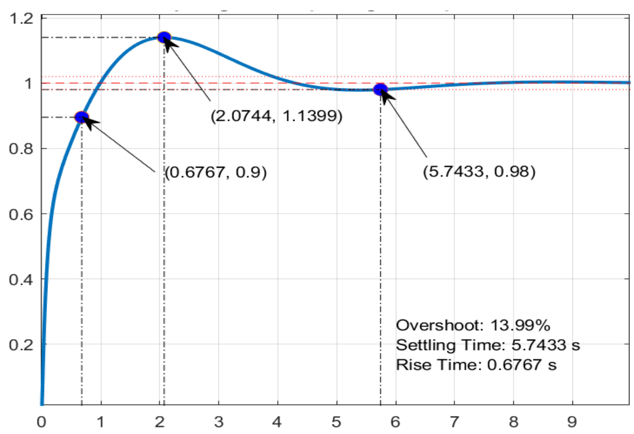

Figure-3. Step response of the system using PID Controller.

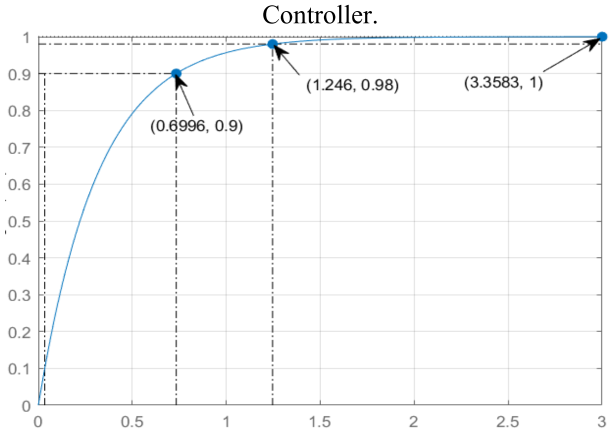

Figure-4. Step response of the system using LQR Controller.

Comments

Steady-State Error: Both controllers meet the requirement with a steady-state error of 0, which is less than 2%.

Rise time: Both controllers have a rise time of less than 2 seconds. The PID controller has a rise time of 0.6767 seconds, while the LQR controller has a rise time of 0.6996 seconds. The difference is not significant.

Maximum overshoot: The PID controller has a maximum overshoot of 13.99%, which does not meet the requirement (< 10%). In contrast, the LQR controller has a maximum overshoot of 0%, meeting the requirement. A large overshoot can lead to system overload, negatively affecting system performance.

Settling time: The PID controller has a settling time of 5.7433 seconds, which does not meet the requirement (< 5 seconds). The LQR controller, however, has a settling time of 1.2464 seconds, meeting the requirement.

Based on the established quality criteria, the LQR controller demonstrates superior performance compared to the PID controller. The LQR controller not only meets all the quality criteria but also has a maximum overshoot of 0 and a shorter settling time compared to the PID controller. Given the superior quality of the LQR controller over the PID system, the research team proceeds with the design and implementation of a practical antenna rotation control system using the LQR controller.

4. DESIGN AND FABRICATION OF THE LQR CONTROLLER FOR THE DC SERVO MOTOR IN THE RADIO POSITIONING SYSTEM

4.1 Simulation of the System Schematic

To simulate the antenna rotation control system using the LQR controller, it is first necessary to identify the components used in the system. To ensure the system functions correctly, the following components are required:

Input device: A potentiometer (RV1 B103 10kΩ) is used to adjust the input voltage to set the desired angle of the motor.

Calibrated dial: This device allows for the adjustment of the potentiometer and makes it easier to monitor the input angle setting.

Control element: The L293D control circuit is employed to control the DC servo motor and protect the system from overcurrent.

Actuator and sensor element: The MG996R DC Servo motor is used to rotate the motor to the set angle and provide feedback on the actual rotation angle.

The system continuously adjusts by comparing the actual rotation angle with the set angle and modifies the PWM signal to ensure the motor precisely reaches the desired angle. According to the simulation results shown in Figure-5, the control error for the system's angle is approximately 0.1 degrees, indicating a high level of accuracy. Thus, the DC servo motor's angle control system has been successfully designed and verified through simulation. With stable simulation results, the system is ready for practical implementation.

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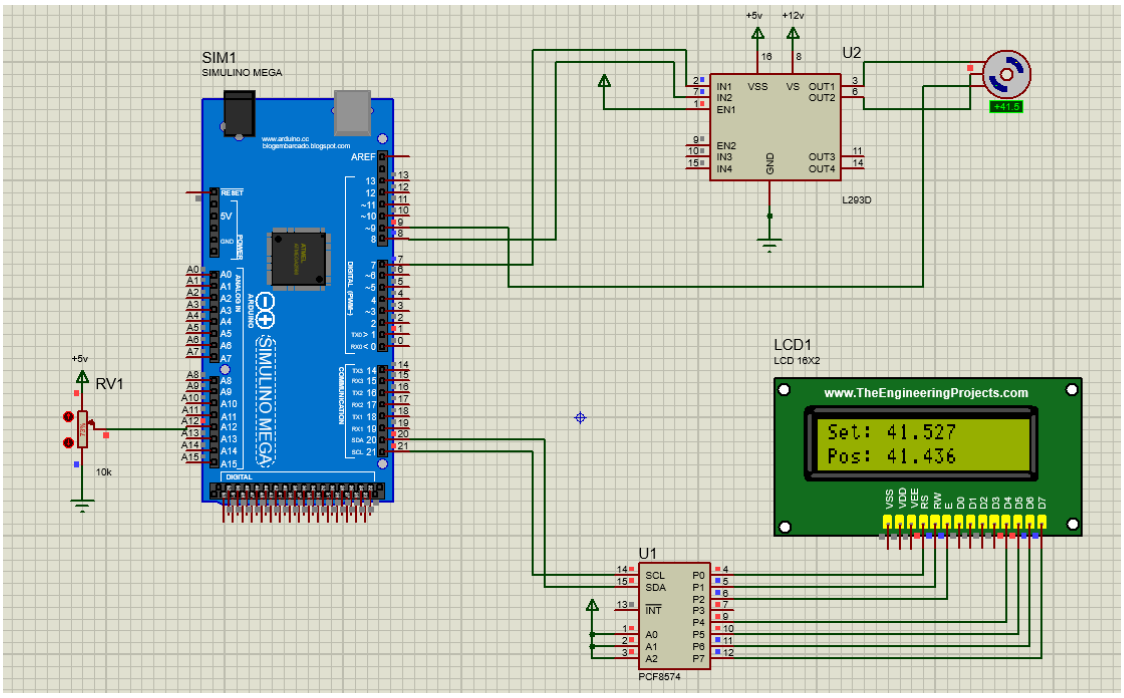

Figure-5. Simulation of the schematic diagram of the Antenna rotation control system using an LQR controller for a DC servo motor.

4.2 System Assembly

Circuit board: A plastic circuit board with dimensions of 16x24 cm is used to mount the Arduino Mega 2560 board. This provides a stable and secure base for the microcontroller and other connected components.

Protective enclosure: The protective enclosure is large enough to accommodate the 15x20 cm plastic circuit board along with other components. Additionally, it has enough space on top to mount the antenna. The enclosure protects the internal components from dust, moisture, and impact, ensuring the system's durability and reliability.

Antenna: The antenna is attached to the shaft of the DC servo motor MG996R, positioned on top of the protective enclosure. This placement ensures optimal signal transmission and reception.

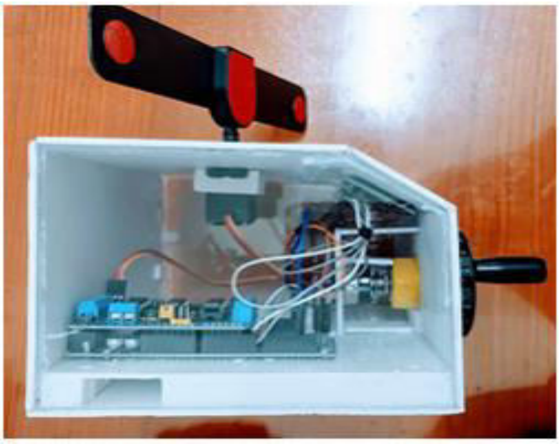

Figure-6. Layout of components in the antenna rotation control system.

Handwheel: The handwheel is mounted on the side of the protective enclosure, allowing the user to easily adjust the potentiometer RV1 to set the desired angle.

LCD Screen: The LCD screen is mounted on the side of the protective enclosure, making it easy for the user to monitor parameters such as the desired angle and the actual rotation angle in real time.

Component layout: The arrangement of these components is illustrated in Figure-6. This layout ensures that all components are easily accessible and that the system operates efficiently and effectively.

4.3 Experimentation and Result Evaluation

Figure-7. Initial position of the antenna.

Practical system testing: Connect the system to the power supply using the power plug located at the back of the protective enclosure. After powering on, wait approximately 3 seconds for the system to complete its startup process.

Set the desired angle for the system using the handwheel located on the side of the protective enclosure. For example, if the handwheel is turned to a 100-degree position, the system will operate, and the antenna will rotate to an angle that closely matches the set angle.

Figure-8. Tracking process of the antenna according to the set angle.

Result evaluation: Observe the actual rotation angle to evaluate the system's performance. The difference between the set angle and the actual angle observed is 100 - 99.898 = 0.112 degrees. This results in a system error of 0.112 % < 2 %, which meets the performance criteria established for the system.

The system demonstrates precise control and accuracy in adjusting the antenna to the desired angle, confirming the effectiveness of the LQR controller in the antenna rotation control system.

5. CONCLUSIONS

The paper presents the research outcomes of the project "Design and Fabrication of an Optimal Controller for Motors in a Radio Positioning System," which includes a detailed description of the design and fabrication process of the antenna rotation control system using a DC servo motor and an LQR controller. Based on the research findings, it can be concluded that the integration of the LQR controller into the radio positioning system has led to a significant improvement in both performance and accuracy compared to traditional control methods. The design and fabrication of the system meet technical requirements and fulfill the criteria for stability and the required quality standards of the system. This project not only provides an enhanced control solution for radio positioning systems but also demonstrates the applicability of optimal control methods in industrial applications and scientific research at the AD-AF Academy.

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