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Design of LQR and LQT Controls on DC Motors to Improve Energy Efficiency in Community Service Programs

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Abstract: *The effectiveness and efficiency of motor speed control are critical for sustainable development, particularly in community-based industries. A control system, defined as a mechanism to regulate, command, and manage a system's state, plays a significant role in optimizing energy usage. DC motors, widely utilized for their linear torque-speed characteristics and high efficiency, are preferred due to their simple control systems and minimal hardware requirements. This research focuses on developing and implementing Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control systems for DC motors, particularly in community service programs aimed at improving energy efficiency in small-scale industries or maritime applications. The study was conducted in several stages, starting with a comprehensive literature review on first-order mathematical modeling, LQR, and LQT methodologies using journal articles, papers, videos, and books. Subsequently, DC motor specifications were obtained from datasheets and converted into first-order mathematical models. The LQR formulation was applied to derive state-space models through MATLAB programming. Experimental results demonstrate that LQR and LQT controls significantly enhance motor speed optimization while minimizing input signals. However, the introduction of noise or disturbances in the system caused instability, resulting in non-uniform motor speed. The study highlights the potential of LQR and LQT controls to improve energy efficiency in DC motor applications within community service programs. These findings can benefit communities by reducing operational energy costs and supporting sustainable technology adoption.*

Keyword: *LQR, LQT, Control System, System Optimization, DC Motor, Community Service, Energy Efficiency.*

Introduction

The effectiveness and efficiency of motor speed control are critical in both industrial and community-based applications. A control system, defined as a tool for regulating, commanding, and managing the state of a system, plays a vital role in achieving these objectives (Magistriaranto & Pratiwi, n.d.). In today's modern industry, the development of control technologies is geared toward creating robust and integrated tools supported by advanced technology to enhance both the quality and quantity of production outcomes.

Understanding and analyzing the characteristics of a system require system identification, which involves modeling the system mathematically based on its component properties (Fahmizal et al., 2018). This process results in a transfer function as the mathematical representation of the system. The transfer function reveals the system's response to various inputs, enabling the formulation of appropriate actions to achieve desired performance. System identification is an experimental approach to deriving dynamic models that represent system behaviors.

DC motors, widely used in various fields, are known for their linear torque-speed characteristics and high efficiency. They also offer simple control mechanisms without requiring complex hardware (Pribadi & Prasetyo, 2019). The motor's characteristics can be represented as first-order mathematical models, which serve as the plant for this study.

This research employs Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control systems. LQR is an optimal control method widely applied in industries, robotics, and other engineering fields (Mandala et al., 2019). Its primary goal is to regulate output (y) to zero with minimal input. This is achieved by designing a feedback gain matrix (K) that minimizes the cost function, an integral of the quadratic form of the state vector (x) and input vector (u) over time (Arrofiq et al., 2021). LQR optimizes system performance indices while balancing performance and effort. Its representation typically involves a state-space approach.

On the other hand, LQT (Linear Quadratic Tracking) is an optimal control method aimed at minimizing performance indices and ensuring that the system (plant) tracks the desired reference trajectory effectively (Muttaqin et al., n.d.). Both LQR and LQT offer significant potential for improving system stability and efficiency.

The primary objective of this study is to transform DC motor data into a first-order mathematical model (transfer function) and implement LQR and LQT control systems to optimize motor speed within a specific timeframe, achieving stability and improved energy efficiency. This approach aligns with community service programs focused on energy conservation and technology dissemination for sustainable practices.

Methodology

1. Research Stages

This study was carried out through several stages to achieve its objectives effectively. The initial stage involved a comprehensive literature review focusing on first-order mathematical models, Linear Quadratic Regulator (LQR), and Linear Quadratic Tracking (LQT). The literature review was conducted through searches for journals, research papers, videos, and books or e-books. Following this, a datasheet for the DC motor was obtained and converted into a first-order mathematical model. Subsequently, the LQR formulation was applied to determine the state-space representation or simulate the system using MATLAB programming, enabling parameter extraction to analyze the system's response. The simulation was carried out under two conditions: normal operation and under noise or disturbance influence.

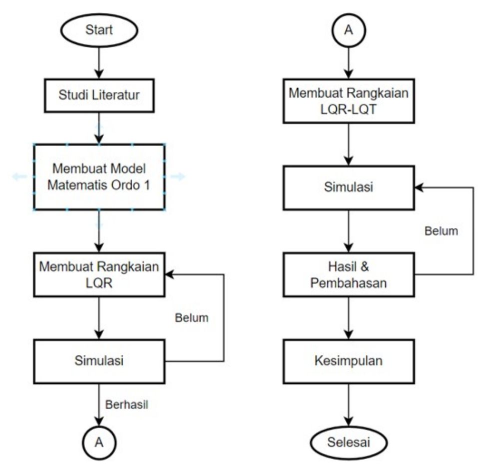

Figure 1. Research Flow Diagram

2. DC Motor

A DC motor is a device designed to convert electrical energy into mechanical energy. This energy conversion occurs through the interaction of two magnetic fields. DC motors are commonly used with a primary focus on rotational speed control (Suryatini & Firasanti, n.d.). In this study, a DC motor serves as the object for analysis, where its datasheet is employed to construct a first-order mathematical model.

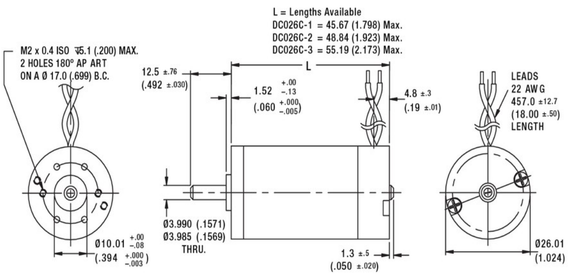

Figure 2. Pittman DC Motor Dimensions

The datasheet used corresponds to the Haydon Kerk Pittman DC motor model DC026C-1 26mm Brushes DC Motor. The datasheet details include specifications for a 12V operating voltage, with key parameters as follows: average torque of 0.010 Nm, average speed of 5450 RPM, average current of 0.92A, average power of 5.8W, no-load speed of 7000 RPM, no-load current of 0.20A, torque constant of 0.0153 Nm/A, voltage constant of 1.6 V/krpm, terminal resistance of 2.89Ω, inductance of 1.63mH, peak current of 4.2A, and a 4:1 gear ratio.

Table 1. Datasheet Haydon Kerk Pittman DC motor

Motor Data	**Units**	**Value**
Rated Voltage	V	12
Rated Torque	Nm	0.01
Rated Speed	Rpm	5450
Rated Current	A	0.92
Rated Power	W	5.8
Rotor inertia (J)	Kg-m2	9.9E-07
Viscous Damping Factor (D)	Nm/(rad/s)	1.2E-06
Terminal Resistance	Ω	2.89
Inductance	Mh	1.63
Constant Torque (K)	Nm/A	0.0153

3. Mathematical Modeling

The mathematical modeling phase involves calculations to derive the mathematical model of the DC motor based on its datasheet. Two modeling approaches were applied, specifically focusing on the first-order model. In control theory, the transfer function is commonly utilized to characterize the input-output relationship of components or systems described by linear, time-invariant differential equations (Ogata, 2010). The equations used in the first-order model are as follows:

$$K = \frac{T}{I} \tag{1}$$

$$G(s) = \frac{K}{Ts + K} \tag{2}$$

Where T is torque, I is current, and K is the torque constant derived by dividing torque by current. The first-order mathematical model for the DC motor is represented as:

$$G(s) = \frac{0.0153}{0.01s + 0.0153} \tag{3}$$

4. Linear Quadratic Regulator Design

The Linear Quadratic Regulator (LQR) is a control method based on state-space representation. LQR uses two control parameters, Q and R, which must be determined to achieve optimal control actions. The performance index of LQR is written as follows (Naidu, 2003):

$$\dot{x}(t)=A(t)x(t)+B(t)u(t) \quad (4)$$

$$y=Cx+Du \quad (5)$$

$$u=-Kx \quad (6)$$

Where y is the controlled output. The cost function is the time integral of a quadratic form of the state vector x and the input vector u:

$$J=\frac{1}{2}\int_{0}^{\infty}\left(x^{T}Qx+u^{T}Ru\right)dt \quad (7)$$

Here, Q is a symmetric positive semi-definite matrix, and R is a symmetric positive-definite matrix. The block diagram of the Linear Quadratic Regulator is illustrated in Figure 3.

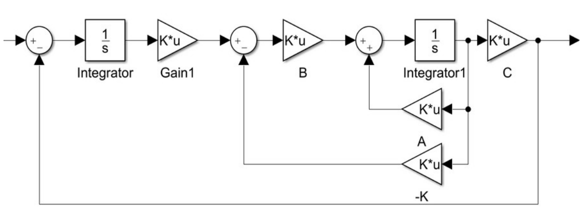

Figure 3. LQR Network

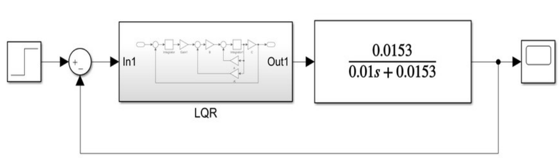

Figure 4. LQR series with order 1 mathematical model plant without noise

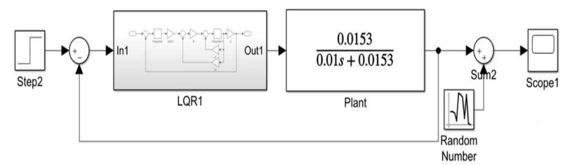

Figure 5. LQR series with order 1 mathematical model plant with noise

5. Linear Quadratic Tracking Design

Linear Quadratic Tracking (LQT) is a control system designed to maintain the output as close as possible to the desired reference with minimal control energy. The linear system for LQT is described as follows:

$$\dot{x}(t)=A(t)x(t)+B(t)u(t) \quad (8)$$

$$y(t)=C(t)x(t) \quad (9)$$

Where x (t) is the state vector of order n, u (t) is the control vector of order r, and y (t) is the output vector of order m.

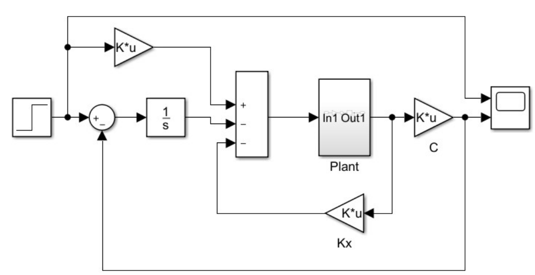

Figure 6. LQT Network

Results and Discussions

The implementation of the methodology outlined earlier yielded simulation results, observed through Matlab's scope. These results demonstrate the effectiveness of using Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods in optimizing the speed and energy efficiency of DC motors, which is particularly relevant for community service programs focusing on energy-efficient maritime technology.

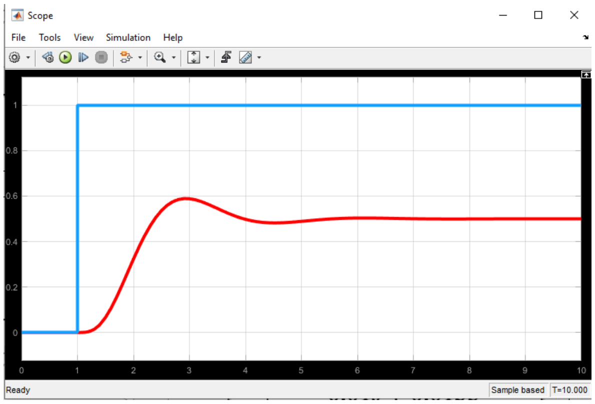

Figure 7. Simulation Results of LQR without Noise

Figure 7 illustrates the simulation results of the LQR control system without noise disturbances. The rise time observed in the figure is approximately 2.5 seconds. The system experiences an overshoot of 16% and requires 5.5 seconds to settle into a stable state. The steady-state error at the given setpoint is about 50%. This performance highlights the system's baseline behavior under ideal conditions.

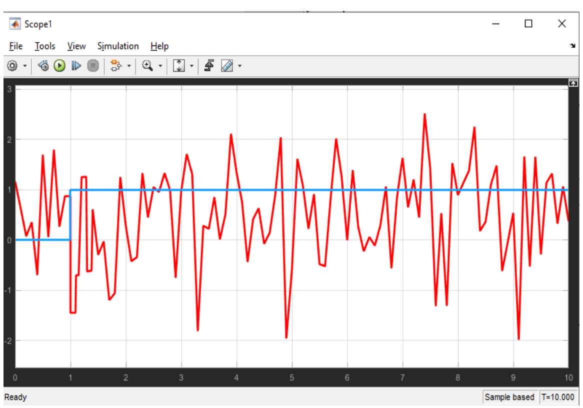

Figure 8. Simulation Results of LQR with Noise

Figure 8 represents the simulation results of the LQR system under noisy conditions. The signal demonstrates significant irregularities due to disturbances, preventing system optimization. These findings highlight the sensitivity of the LQR controller to noise, which could impact its application in real-world scenarios like maritime environments with fluctuating external factors.

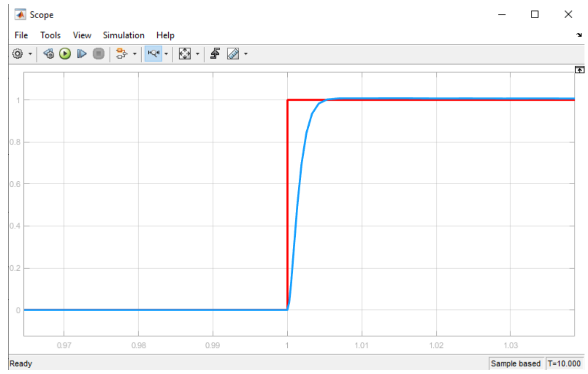

Figure 9. Simulation Results of LQT without Noise

Figure 9 shows the results of the LQT simulation under ideal conditions. The rise time is significantly improved, taking only 1.005 seconds. The system successfully reaches the setpoint with no steady-state error (0%). This demonstrates the LQT controller's superior ability to achieve optimal speed performance with minimal control input.

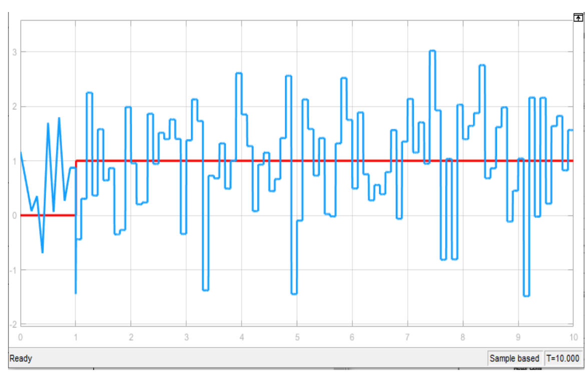

Figure 10. Simulation Results of LQT with Noise

Figure 10 displays the results of the LQT simulation under noisy conditions. The signal becomes highly erratic, showing continuous overshoots and undershoots with varying percentages relative to the setpoint. This result underscores the challenge of maintaining system stability and efficiency in noisy environments.

1. Analysis of LQR and LQT Performance

The experiments using both LQR and LQT controllers highlight their respective strengths and limitations. While both controllers effectively optimize motor speed under ideal conditions, their performance deteriorates significantly when subjected to noise disturbances. The instability caused by noise can lead to suboptimal motor speeds and irregular signal behavior. This finding is crucial for designing energy-efficient DC motor systems tailored for community service projects, such as enhancing maritime energy efficiency.

Conclusion

From the discussion and analysis conducted, it can be concluded that the optimization control systems using LQR and LQT methods effectively enhance the speed optimization of DC motors with minimal input energy. These systems can play a vital role in community service programs aimed at improving energy efficiency in maritime applications, particularly in ship engine systems using flowmeter sensors.

However, the presence of noise significantly affects the system's performance, leading to instability and irregular motor speed. Future research could explore noise mitigation strategies or the implementation of more robust control techniques to enhance the applicability of LQR and LQT controllers in real-world scenarios, ensuring their reliability in community service initiatives.

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