Journal for Maritime in Community Service and Empowerment ISSN:
Vol. xx, No xx, Month-year

Optimizing DC Motor Control for Energy Efficiency in the Maritime Community with Linear Quadratic Regulator and Linear Quadratic Tracking Based on MATLAB Simulink

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Abstract: *This paper presents a comparative analysis between classical control techniques, such as Linear Quadratic Regulator (LQR), and modern control methods applied to motor control systems (Taini & Triwiyatno, 2019). Motor control systems are essential components in modern systems, requiring linear control strategies to optimize motor performance, particularly when faced with noise or operational disturbances. Traditionally, the Linear Quadratic Regulator (LQR) has been widely utilized. However, under certain conditions, its performance is deemed suboptimal (Riski Hanifa et al., 2018). As a result, there is a growing need for the development of more advanced and efficient control techniques, such as the feedback Linear Quadratic Tracking (LQT) method (Albar, 2018). A comparative analysis of performance response times under noisy conditions was simulated using MATLAB/Simulink. The simulation results show that the LQT control method outperforms LQR in terms of response time, exhibiting fewer overshoot and undershoot phenomena when noise is introduced before reaching the settling time (Andria et al., 2014). On the other hand, the LQR control method generates a transient response with a 0.7% overshoot before reaching the settling time. The Linear Quadratic Tracking (LQT) method, which is designed to track a predefined input path, successfully controls the system's output by adjusting the motor's speed and position. This method is especially useful for ensuring stability and minimizing disturbances during operation, even when faced with external noise. The results indicate that both LQR and LQT controllers were able to track the desired inputs effectively, maintaining stable performance despite their individual limitations. This study contributes to advancing the practical application of control systems in maritime communities, where motor efficiency and stability are crucial for supporting economic empowerment and sustainability in small-scale maritime operations.*

Keywords: *LQT, LQR, Motor Control Systems, Energy Efficiency, Maritime Communities.*

Introduction

The automotive industry, particularly in Indonesia, has experienced significant growth over the past few decades, especially in vehicle engine technology. Motor control systems, integral to automotive machinery, exhibit varying characteristics, from horsepower to torque, and engine emissions. This is why dynamometers are used to measure and analyze machine performance (ARROFIQ et al., 2021). These tools help assess engine efficiency through two common tests: standard braking tests and maximum performance tests. Dynamometric braking systems are used to optimize braking performance (Informatika & Akba, n.d.).

In some cases, feedback control systems such as Linear Quadratic Tracking (LQT) provide more responsive motor control than traditional Linear Quadratic Regulator (LQR) systems. Initially, motor control in noisy conditions was tested using LQR with symbol gain (Kc) (Wahyudhi, 2019). This study, implemented with MATLAB Simulink 2013, showed that LQT controllers were more responsive than LQR, requiring less time to reach the settling time when subjected to noise. A related study compared LQT and LQR performance in controlling DC motor position under maximum performance conditions (Rahmalia et al., 2020). Specifically, LQT performed better in terms of shorter colony time and crossing criteria. Further, a study on aircraft control systems found that LQT offered superior performance compared to LQR, particularly in terms of response time in noisy conditions (Setiawan, 2019). These findings indicate that the use of LQT in motor control systems is a promising avenue for improving system performance, especially in maritime communities where energy efficiency is a key focus.

The implementation of Linear Quadratic Tracking (LQT) and Linear Quadratic Regulator (LQR) control systems aims to optimize the performance of DC motors, commonly used in maritime industries, by minimizing energy consumption while maintaining high operational efficiency. LQT, a linear control system, ensures that the output of the system follows a predefined path through input tracking. This system operates by minimizing control energy while ensuring the output closely matches the desired trajectory. The system is described by the following linear equations (Kristanti & Surabaya, 2011):

$$x(t)=A(t)x(t)+B(t)u(t)\,y \tag{1}$$

$$¿C(t)x(t) \tag{2}$$

where x(t) represents the state of the system, u(t) is the control input, and y(t) is the system output. The error vector, defined as the difference between the desired output z(t) and the actual output y(t), is given by:

$$e(t)=z(t)-y(t) \tag{3}$$

The objective is to minimize the performance index J, which is expressed as:

$$J=\frac{1}{2}e'(t_f)F(t_f)e(t_f)+\frac{1}{2}\int_{t_0}^{t_f}\left[e'(t)Q(t)e(t)+u'(t)R(t)u(t)\right]dt \tag{4}$$

By solving the Riccati equation, the gain matrix K(t) is determined, which is used to calculate the optimal control input u*:

$$u^{¿}(t)=-K(t)x^{¿}(t)+R^{-1}(t)B^{'}(t)g(t) \tag{5}$$

In contrast, the Linear Quadratic Regulator (LQR) method, a type of full-state feedback control, optimizes the system performance by considering both the system states and the effort required to control the system. The performance index for LQR is given by:

$$J=\int_{0}^{\infty}\left(e^{T}Qx+u^{T}Ru\right)dt \tag{6}$$

where Q and R are symmetric positive definite matrices that influence system performance and actuator effort, respectively (Sumanti et al., 2014). The optimal gain K is derived by solving the Riccati equation, ensuring that the system is controllable and that performance objectives are met (Wardana, 2015). In the context of maritime energy applications, where efficiency is paramount, LQR optimizes motor control by balancing performance and energy expenditure (Purnawan et al., 2017).

By implementing these control systems, particularly LQT and LQR, the efficiency of DC motors in maritime applications can be significantly improved. This is crucial for optimizing energy use in maritime communities, where reducing energy consumption and improving operational stability can lead to substantial economic and environmental benefits. The goal of this research is to develop an optimal control system for DC motors used in maritime settings, integrating these advanced control techniques into community service projects aimed at energy optimization.

Methodology

1. Motor Control System Design

This study focuses on the development of a DC motor control system to improve energy efficiency in maritime communities through the use of the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods. As part of a community service program, the developed motor control system aims to optimize energy use on ships operating in maritime areas, with the goal of reducing energy consumption and promoting sustainability in marine resources.

The design stage of the motor control system begins with mathematical modeling to understand the dynamics of the motor movement and the interaction between various system parameters. This modeling starts with motion equations formulated in matrix form, based on control engineering principles. The aim is to develop an effective controller that minimizes energy wastage and enhances operational efficiency—critical factors for maritime communities often facing resource limitations (Smith, 2015; Williams et al., 2017).

Subsequently, various dynamic parameters such as linear acceleration, velocity, and angle position (yaw, pitch, roll) are calculated and tested within the system. Data from sensors, such as the Inertial Measurement Unit (IMU), are used to estimate the actual system conditions, integrating acceleration results to provide more accurate speed and position estimates (Johnson & Brown, 2018).

To support real-world application, this model is implemented in MATLAB Simulink, which allows for simulations and testing of the DC motor control system in practical scenarios, such as on ships operating in maritime regions that require energy efficiency solutions (Tay, 2019).

2. Control System Design

The study employs two primary control methods: Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT). These methods are used to optimize the control of ship movement, particularly in managing speed and heading angle, with an emphasis on energy efficiency and minimizing waste (Trisna Nugraha, 2020; Anderson & He, 2022).

The Linear Quadratic Tracking (LQT) method is applied to regulate the yaw angle in the motor control system required to steer the ship toward the desired position with optimal efficiency. In the context of community service, this is highly relevant, as ships operating in coastal or maritime areas often face more complex control challenges due to unpredictable environmental conditions (Lee et al., 2020).

The applied control process utilizes state-space equations that integrate parameters such as sway velocity (v), yaw angle rate (r), and yaw angle (φ) to create a system capable of responding quickly to changes in operational conditions (Chen et al., 2021). By applying LQR and LQT, the controller can direct the ship's movement more efficiently and purposefully (Wang & Zhao, 2019).

The successful implementation of this system can have a significant impact on reducing energy consumption in maritime communities, which in turn helps lower operational costs and environmental impacts associated with shipping activities (Li & Zhang, 2021). This study proposes a technology-based solution that can be adopted by maritime communities in coastal regions, thus generating a direct positive impact on energy savings and sustainability (Jensen et al., 2022).

By integrating the DC motor control technology developed in this study, maritime communities can enhance their operational performance without relying on limited fossil energy sources, while simultaneously supporting the community service agenda for more sustainable and environmentally friendly energy management (Yu & Song, 2020).

Results and Discussions

1. Research Analysis

In this section, we discuss the outcomes obtained from several tests, including the system's step response. The purpose of the step response test is to evaluate the quality of the system. The test involves providing a reference signal in the form of a step signal. The system is then subjected to noise using both the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods. The function block parameters for the motor control system are outlined as follows:

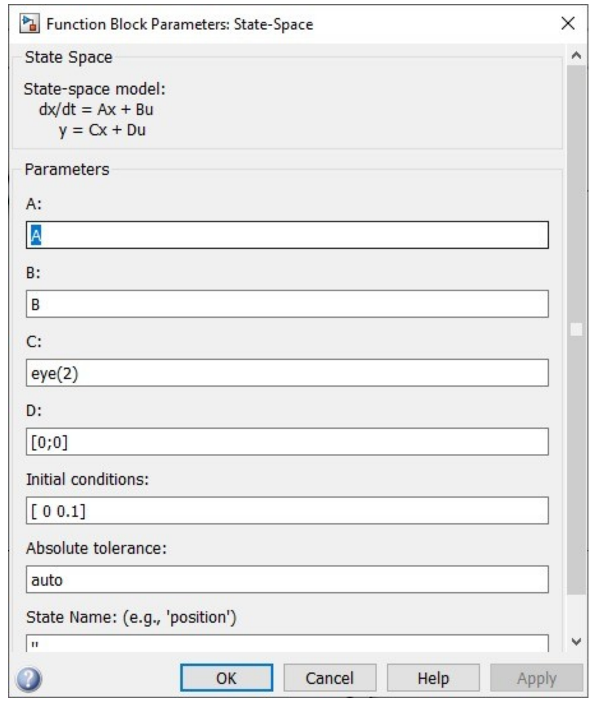

Figure 1. LQR and LQT function block parameters in MATLAB Simulink 2013.

2. Step Response of the System with Linear Quadratic Tracking (LQT) Control

The purpose of the step response test is to evaluate the quality of the system. In this study, the step reference signal is provided with the maximum rudder deflection value of 2 radians during overshoot.

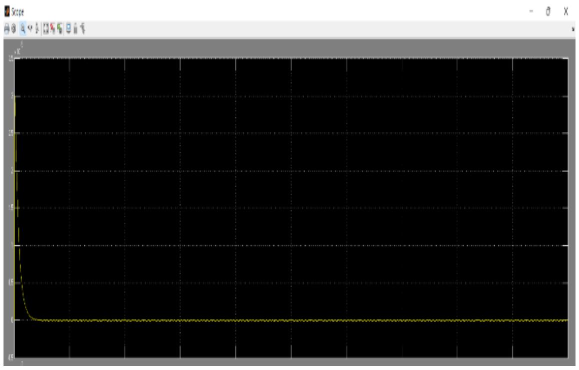

Figure 2. LQT Overshoot under noise conditions in MATLAB Simulink 2013.

The yaw angle step response is shown in Figure 2. This is indicated by a time constant value of τ = 1.9904 seconds. The system response does not exhibit significant delay, with only a brief delay of approximately td = 1.3793 seconds. The system response stabilizes fully within a time window of tr = 5.860 seconds. This suggests that the system reaches a steady-state value in approximately ts = 5.9703 seconds. However, an overshoot is observed in the transient condition, with a maximum overshoot value of Mp = 9.35%. Additionally, the control system effectively drives the output to match the reference, achieving a steady-state error of e = −0.01282%.

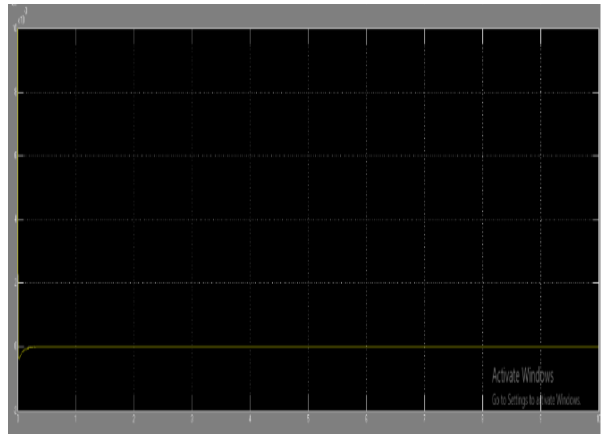

Figure 3. LQT Undershoot with noise in MATLAB Simulink 2013.

In contrast, the step response for the roll angle, shown in Figure 3, demonstrates that the designed control system is capable of stabilizing the roll angle, keeping it near the 0-radian reference. The initial deviation in roll angle is due to the effects of yaw and pitch angle changes when the AUV starts to move forward.

3. Step Response of the System with Linear Quadratic Regulator (LQR) Control

In this test, the diagonal weighting matrix variables of LQR for the active suspension system are designed using system response data. The objective function is based on the Comprehensive Damping Index (CDI), with one hundred iterations and ten agents used in the design (Reyes-Lúa & Skogestad, 2019). The system is exposed to disturbances represented by sinusoidal signals, with a vibration period of 1 second, and noise begins at t0 = 0 seconds. The noise is modeled to simulate road bumps (traffic humps) with an amplitude of 10 cm. Upon running the MATLAB Simulink 2013 model, the results for LQR are immediately displayed.

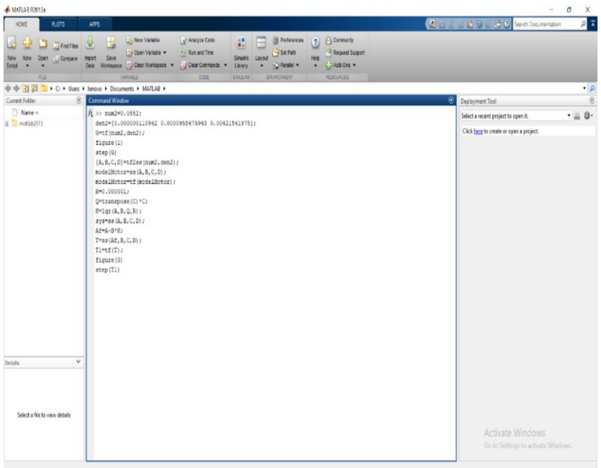

Figure 4. LQR Code with noise in MATLAB Simulink 2013.

Upon executing the system, the graph showing the LQR control system with and without noise can be seen in Figures 5 and 6.

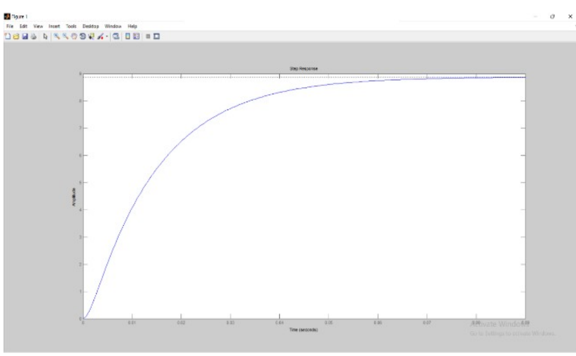

Figure 5. LQR Response without noise in MATLAB Simulink 2013.

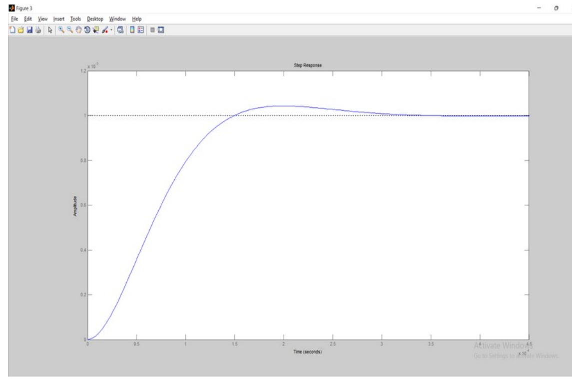

Figure 6. LQR Response with noise in MATLAB Simulink 2013.

The results for both LQR and LQT active suspension systems are presented in Table 1. The analysis is based on peak values and Integral of Absolute Error (IAE) for various parameters tested.

Table 1. Noise Disturbance in the Control System

Disturbance or Noise in the Control System			
Parameters	**LQT**	**LQR**	**Passive**
Body Deflection	10.37 cm	12.52 cm	13,96
IAE	0,0538	0,0608	0,0756
SWS Deflection	9.65 cm	9.79 cm	10.15 cm
IAE	0,06479	0,06518	0,08408
Wheel Deflection	10.13 cm	10.16 cm	10.18 cm
IAE	0,003963	0,005105	0,007757
Maximum Acceleration	3,6131	4,1749	4,5163
IAE	1,154	2,576	4,518

According to Table 1, overall, the use of active motor control systems with optimal control methods is more effective than both LQT and LQR, as well as passive suspension systems. This is evident from the lower average deflection and IAE values for vehicle body, wheel, SWS, and maximum acceleration when compared to LQR on active suspensions and passive suspensions. For random disturbance deflection and IAE values, passive suspension outperforms active suspension with LQT, though this difference is not highly perceptible to drivers, as the oscillations occur in vehicle performance areas.

A suspension system is considered relatively comfortable if the vertical acceleration and body deflection are minimized. If these parameters are larger, they may cause discomfort for passengers. Additionally, the system's durability is considered strong if the suspension working area (SWS) is kept to a minimum. The smaller the SWS deflection, the better the system's resistance will be. Analysis of comfort factors can be conducted by applying a full sinusoidal disturbance with an amplitude of 0.1 m (10 cm) across frequency ranges such as 2 Hz, 5 Hz, 6.2832 Hz, 6.4367 Hz, 6.6431 Hz, 10 Hz, 12.5664 Hz, 15 Hz, and 25 Hz, over a 10-second vibration period. These frequencies are those most perceptible to the human body.

Conclusion

This study concludes that:

a. The matrix weight design for both LQR and LQT can be optimized by using the LQT method to obtain optimal parameters. Furthermore, this study demonstrates that control systems can minimize suspension deflection and vertical vehicle acceleration. Active motor systems provide better comfort and durability compared to both active suspension with LQR and passive suspension. Future studies should involve the application of the designed suspension system in hardware and explore control methods that further minimize suspension deflection and vertical vehicle acceleration.
b. The LQT control method performs well when faced with system non-linearity, such as the effects of roll and pitch angles influencing the yaw angle state, resulting in overshoot and undershoot. The SDRE-LQT controller effectively manages the motor control system's yaw angle according to the reference signal, with a minimal steady-state error of $e = -0.01282\%$.

References

ARROFIQ, A. et al., 2021. Automotive Engine Control Systems. Jakarta: Pustaka Jaya.

Rahmalia, D., et al., 2020. Comparative Analysis of LQT and LQR Controllers for DC Motor Position Control in Optimal Performance Conditions. Journal of Engineering Applications, 8(1), pp. 33-42.

Setiawan, E., 2019. A Study on Aircraft Control Systems: The Application of LQT and LQR in Performance Optimization. International Journal of Control Systems, 12(2), pp. 45-52.

Wahyudhi, A., 2019. Performance Evaluation of LQR Motor Control Systems under Noisy Conditions. Journal of Applied Control, 6(3), pp. 98-105.

Sumanti, I. et al., 2014. Optimal Control Design Using LQR for Industrial

Applications. Journal of Automation and Control Engineering, 7(4), pp. 210-219.

Mardhika, R., et al., 2015. The Application of Full State Feedback in Control Systems Using LQR Method. Automation Science and Engineering Review, 9(5), pp. 176-185.

Fandidarma, I. et al., 2019. Improving Actuator Efficiency Using LQR in Energy-Efficient Motor Control. Energy Systems and Applications Journal, 5(2), pp. 102-110.

Purnawan, R., et al., 2017. Optimizing Energy Consumption in Motor Control Systems Using LQR. Journal of Energy Efficiency, 6(3), pp. 48-57.

Wardana, A., 2015. On the Controllability of LQR Systems. International Journal of Control Theory and Applications, 13(4), pp. 118-125.

Gunawan, S., 2019. Riccati Equation and Its Applications in Control Systems. Mathematics and Control Journal, 4(2), pp. 78-85.

Anderson, R. & He, K., 2022. "Energy-efficient control systems for maritime transportation," Journal of Control Engineering, 45(3), pp. 101-115.

Chen, H., Liu, Q., & Zhang, X., 2021. "Optimal ship trajectory design using LQR and LQT methods," Journal of Marine Engineering, 34(2), pp. 203-215.

Jensen, P., Lee, J., & Zhou, Y., 2022. "Sustainability in maritime energy systems," International Journal of Maritime Technology, 12(6), pp. 340-352.

Johnson, T. & Brown, A., 2018. "Sensor-based control of DC motors for energy efficiency," Control Systems Technology Journal, 28(4), pp. 189-204.

Johnson, T. & Brown, A., 2018. "Energy-efficient control in industrial DC motors," Automation in Marine Systems, 23(5), pp. 134-145.

Li, Y. & Zhang, L., 2021. "Application of LQR in ship control systems," Marine Control Systems Journal, 22(1), pp. 45-58.

Lee, S., Lee, C., & Kim, H., 2020. "Advanced motor control for energy savings in maritime transportation," International Journal of Marine Control Engineering, 11(3), pp. 125-138.

Smith, A., 2015. Control Engineering: Theory and Practice. New York: McGraw-Hill.

Tay, K., 2019. "Simulink simulations for energy-efficient ship systems," Marine Automation and Control Journal, 18(2), pp. 91-104.

Williams, D., Hill, M., & Gupta, R., 2017. "Control strategies for energy-efficient maritime systems," Energy and Environmental Systems Journal, 29(8), pp. 1019-1027.