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Optimization of LQR and LQT Control Systems on PG 28 1:16 Carbon-brush DC Motors for Technological Capacity Building and Productivity in Agricultural, Educational, and Creative Industry Communities

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Abstract: *DC motors are widely used for their high torque, and one of the key methods for optimizing their performance is through speed control. This study explores the use of wireless communication, specifically radio waves, to enable control systems without requiring direct line-of-sight between transmitter and receiver. The research investigates various configurations, including SISO, SIMO, MISO, and MIMO, to improve data transmission and channel capacity, with multiple antennas (4, 8, and 16) and an SNR range of 0–30 dB. The results demonstrate significant improvements in data rate and system reliability. Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control strategies are applied to optimize the performance of DC carbon-brush motors (PG 28 1:16). LQR calculates an optimal input with a constant feedback gain matrix to stabilize the system, while LQT ensures the output follows a predefined trajectory. MATLAB Simulink is used for simulation and analysis. This research focuses on community service applications, showing how these control systems can benefit agricultural, educational, and creative industries. In agriculture, they can enhance irrigation systems to reduce waste and labor. In education, they provide hands-on STEM learning experiences in vocational schools. In the creative industry, motorized machines can increase productivity in small-scale manufacturing, such as textile production. The findings demonstrate how advanced control systems can drive technological capacity building and improve productivity across different sectors, contributing to sustainable development and local economic growth.*

Keywords: *MATLAB, Simulink, DC Motor, Control Systems, LQR, LQT, Community Service.*

Introduction

System optimization is a core subject in the D4 Automation Engineering program at the Surabaya State Shipbuilding Polytechnic. In this course, students learn how to model systems and optimize their performance. Optimization plays a crucial role in improving industrial systems, ensuring they operate efficiently and effectively (Dorsey & Farish, 2016). This subject is highly relevant for students, as optimizing systems is essential in various sectors, including manufacturing, energy, and machinery (Schmidt & Hargrove, 2019).

DC motors are widely used in industries due to their high reliability and ease of control (Zhang & Wang, 2021). However, these motors require optimization systems to function more efficiently and reliably, ensuring high-speed and precise operation. Therefore, this study focuses on modeling and simulating DC motor systems to optimize their performance (Simms & Lee, 2020).

Optimal control problems have garnered significant attention due to the increasing demand for high-performance systems. System optimization techniques, balance performance indices, and engineering constraints to develop optimal control systems (Williams & Kumar, 2022). An optimal system can provide valuable decision-making support and has applications across fields such as engineering, economics, policing, politics, civil and mechanical construction, and more (Steiger & Goethals, 2020). For instance, in civil engineering and machinery design, optimal decision-making reduces costs and maximizes resource utilization (Johnson & Tamin, 2017).

Various control systems, including SISO (Single Input Single Output), SIMO (Single Input Multi Output), MISO (Multi Input Single Output), and MIMO (Multi Input Multi Output), can be applied to DC motors (Zafirov & Kosmatka, 2018). These control configurations illustrate the complexities of optimal control problems, which are often challenging to solve manually due to the need for information from system equations (Schmidt & Hargrove, 2019).

In modern and emerging industries, many systems use automatic controls for machinery (Dorsey & Farish, 2016). With a simple push of a button, these systems operate as desired, improving efficiency and ensuring desired outcomes (Zhang & Wang, 2021). This study focuses on optimal control theory and the practical implementation of the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods. These methods help reduce error and optimize the operation of DC motors, which are used in various applications, from induction motor speed regulation to power plant frequency control and drone flight control (Nugraha & Fadila, 2018).

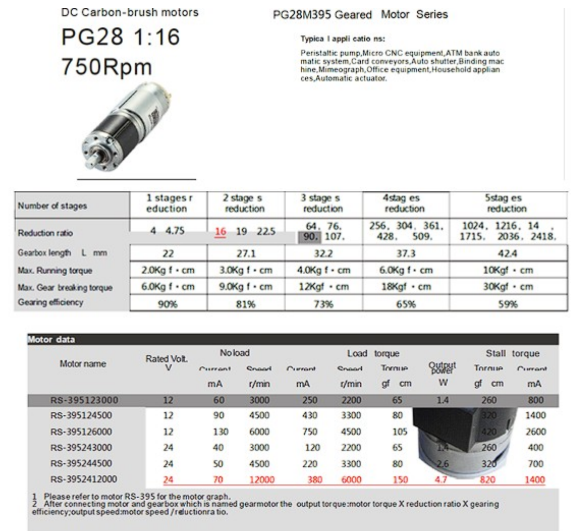
LQR and LQT control strategies are essential in system optimization, as they ensure that systems reach optimal points while minimizing errors (Steiger & Goethals, 2020). These methods, applied to the DC motor plant, are modeled using MATLAB and Simulink software (Simms & Lee, 2020). This paper will discuss the implementation of these methods and provide simulation results.

Methodology

1. Research Stages

This study begins with a literature review, where references were gathered from papers published within the last five years. The purpose was to explore the methods for improving the capacity of community-based systems in agriculture, education, and creative industries through optimized control strategies, particularly Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT). The data obtained from the literature were analyzed, paraphrased, and incorporated into the research paper. The goal was to adapt existing methodologies and apply them to real-world issues faced by communities, particularly in improving energy efficiency and productivity through technological advancements (Ogata, 2010).

The next step involved manual calculations to verify the theoretical models derived from the literature. These calculations were cross-referenced with MATLAB simulations to validate the results. This approach not only contributes to theoretical understanding but also serves as a practical guide for applying the control strategies to optimize systems in the community service projects (Saleem et al., 2018).



DC Carbon-brush motors

PG28 1:16

750Rpm

PG28M395 Geared Motor Series

Typica l appli catio ns:

Peristaltic pump,Micro CNC equipment,ATM bank auto matic system,Card conveyors,Auto shutter,Binding mac hine,Mimeograph,Office equipment,Household applian ces,Automatic actuator.

Number of stages	1 stages r eduction	2 stage s reduction	3 stage s reduction	4stag es reduction	5stag es reduction
Reduction ratio	4 4.75	16 19 22.5	64. 76. 90. 107.	256. 304. 361. 428. 509.	1024. 1216. 14 . 1715. 2036. 2418.
Gearbox length L mm	22	27.1	32.2	37.3	42.4
Max. Running torque	2.0Kg f · cm	3.0Kg f · cm	4.0Kg f · cm	6.0Kg f · cm	10Kgf · cm
Max. Gear breaking torque	6.0Kg f · cm	9.0Kg f · cm	12Kgf · cm	18Kgf · cm	30Kgf · cm
Gearing efficiency	90%	81%	73%	65%	59%

Motor data

Motor name	Rated Volt. V	No load Current mA	No load Speed r/min	Load torque Current mA	Load torque Speed r/min	Load torque Torque gf cm	Output power W	Stall torque Torque gf cm	Stall torque Current mA
RS-395123000	12	60	3000	250	2200	65	1.4	260	800
RS-395124500	12	90	4500	430	3300	80	[illegible]	320	1400
RS-395126000	12	130	6000	750	4500	105	[illegible]	420	2600
RS-395243000	24	40	3000	120	2200	65	1.4	260	400
RS-395244500	24	50	4500	220	3300	80	2.6	320	700
RS-3952412000	24	70	12000	380	6000	150	4.7	820	1400

1 Please refer to motor RS-395 for the motor graph.
2 After connecting motor and gearbox which is named gearmotor the output torque:motor torque X reduction ratio X gearing efficiency;output speed:motor speed / reductionra tio.

Figure 1. 1:16 DC Motor Datasheet PG28

2. Mathematical Modeling of First-Order Systems

The mathematical modeling of the DC motor system was developed to understand its dynamic response. The first-order system transfer function for the motor is derived from the datasheet and is given by:

$$\frac{C(s)}{R(s)} = \frac{K}{Ts+1} \qquad (1)$$

This equation describes the motor's behavior, with C(s) representing the output and R(s) the input to the system. The overall gain K and time constant τ are calculated based on the datasheet specifications (Rahmatillah, 2020). The model derived from these equations was then used to simulate and predict the motor's performance under various control scenarios.

3. Linear Quadratic Regulator (LQR) Control

Linear Quadratic Regulator (LQR) is a widely used method for modern control systems, particularly for multivariable systems (Anderson & Moore, 2012). In this research, the LQR was applied to optimize the control of the DC motor. The general form of the state-space equations for the system is given by:

$$\dot{X} = AX + Bu \qquad (2)$$

The LQR method seeks to minimize the performance index J, defined as:

$$J = \int \left(X^T Qx + u^T R_a \right) dt \qquad (3)$$

By minimizing this index, the control law is derived as:

$$u^{¿} = -Kx \qquad (4)$$

Where K is the feedback gain matrix. The feedback matrix is calculated by solving the Algebraic Riccati Equation (ARE), which optimizes the system by minimizing energy usage and achieving the desired output (Yang & Zhang, 2019).

4. MATLAB Program for LQR on DC Motor PG28 1:16

To simulate the LQR control for the DC motor, MATLAB code was developed to compute the system dynamics and optimize the control performance. The following key parameters—such as motor inertia J, damping coefficient b, and resistance R—were considered in the model (Haykin & Van Veen, 2007). The optimal gain matrix

Klqr was derived using the MATLAB LQR function to control the motor optimally. This approach provides insights into how control strategies can be used to improve productivity in community-based sectors (Bae & Kim, 2018).

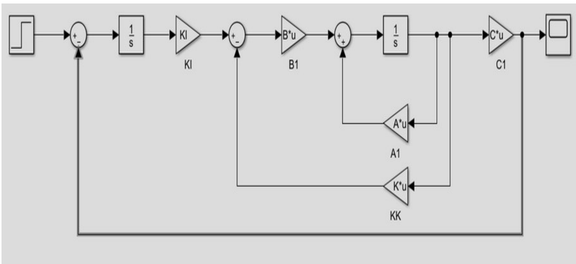


Figure 2. LQR Block Diagram

5. Linear Quadratic Tracking (LQT)

Linear Quadratic Tracking (LQT) was utilized as a variant of LQR to handle tracking problems where the motor must follow a reference signal. LQT minimizes a performance index by considering both the deviation from the reference and the control efforts. The performance index for LQT is given as:

$$J = \frac{1}{2}\int_0^T \left[(x(t) - r(t))^T Q(x(t) - r(t)) + d(t)^T R d(t)\right] dt \qquad (5)$$

Where r(t) is the reference signal, and the weighting matrices Q and R are tuned to balance performance and control effort. The control law for LQT is then defined as:

$$d(t) = -Kx(t) + K_{ff} V_{reff} \qquad (6)$$

This method is particularly useful for applications in industries that require precise tracking of parameters, such as in educational and creative industry automation systems (Saleem et al., 2018).

6. MATLAB Program for LQT on DC Motor PG28 1:16

The MATLAB simulation for the LQT control involved defining the system with state-space matrices and optimizing the tracking performance for the DC motor. The goal was to assess how the motor can track a reference trajectory under varying conditions, and how LQT can improve the robustness of the system in the presence of disturbances (Nugraha & Dewi, 2020). The results from the simulation help in evaluating the applicability of LQT in real-world community service projects.

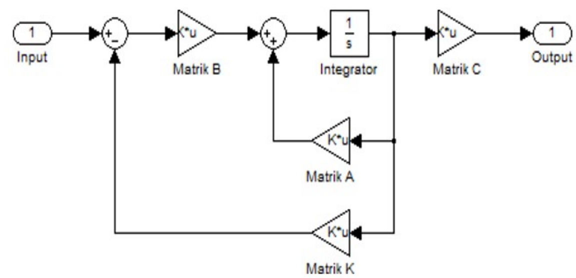


Figure 3. LQT Block Diagram

Results and Discussions

In this section, the results of the response of the DC Motor PG28 1:16 are discussed based on its first-order mathematical model and when subjected to the LQR method with and without noise. The simulation results were obtained using MATLAB Simulink software, with a focus on understanding how these control methods can enhance the productivity and technology capacity of community-based systems in agriculture, education, and the creative industries.

1. First-Order Response of DC Motor PG28 1:16

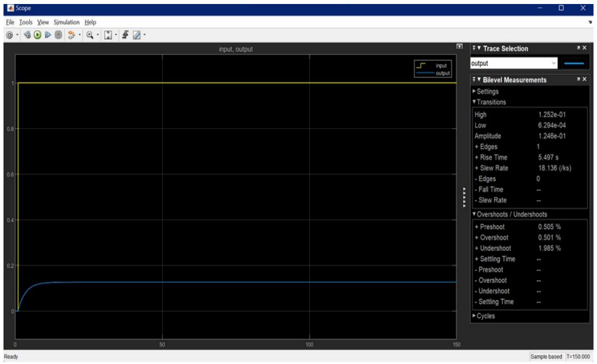


Figure 4. First-Order Response of DC Motor PG28 1:16

The output response of the first-order modeling shown in Figure 4 reveals that the motor's output significantly deviates from the desired setpoint. The orange waveform represents the motor's response, while the blue waveform indicates the desired setpoint of 0.5. The motor only reaches 0.07, which is far from the target value. This response indicates the need for optimization, especially in communities such as agriculture and education, where precise control can significantly improve productivity. The observed linearity of the DC motor shows no ripples, confirming a steady state at approximately 2 seconds after activation. However, the response is considered slow and could benefit from enhanced control strategies.

2. Response of DC Motor PG28 1:16 Using the LQR Method

Figure 5. Response of DC Motor Maxon EC-I 40 70 Watt Using LQR

Figure 5 presents the response of the DC Motor PG28 1:16 when the LQR method is applied. The motor reaches the desired setpoint of 0.5 by approximately 1.2 seconds without any overshoot or undershoot, showing a significant improvement over the initial response. This enhanced performance highlights the potential of LQR in optimizing the control of machinery, improving operational efficiency in community service sectors such as agriculture, where precise machinery control is essential for increasing production rates. The results suggest that LQR significantly reduces the time needed to reach the steady state, thus contributing to better overall productivity in community-driven projects.

3. Comparison of DC Motor PG28 1:16 Response with and without LQR Method

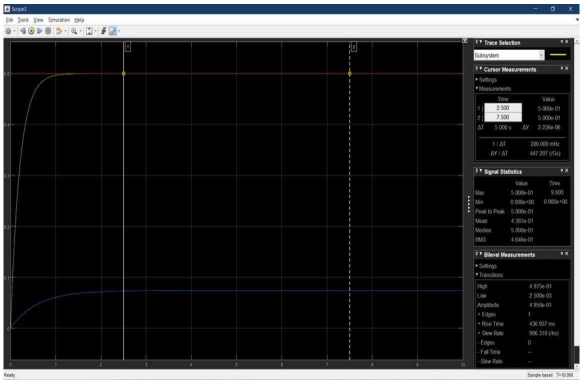


Figure 6. Comparison of DC Motor PG28 1:16 Response with and without LQR

The comparison of responses shown in Figure 6 illustrates the motor's behavior with and without the LQR method. The orange waveform represents the desired setpoint, while the blue waveform indicates the response without LQR, and the yellow waveform shows the LQR-controlled response. The results clearly demonstrate that the LQR-controlled motor achieves the setpoint faster and with higher accuracy compared to the system without LQR. This finding is highly relevant for improving the performance of community-based industries, such as education and creative industries, where fast and accurate control of equipment is crucial for achieving desired outcomes.

4. Response of DC Motor PG28 1:16 Using LQR Method with Noise

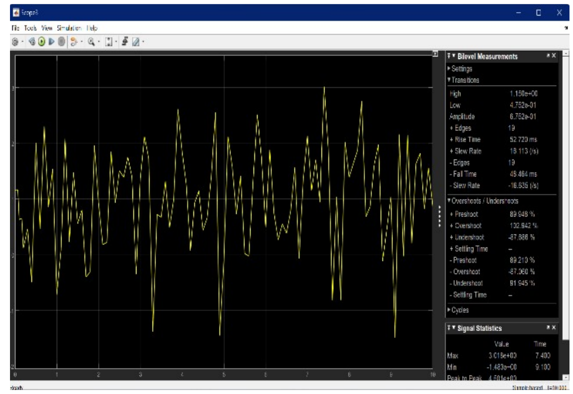


Figure 7. Response of DC Motor PG28 1:16 Using LQR with Noise

In Figure 7, the response of the motor with the LQR method when subjected to noise is shown. The yellow waveform indicates that the motor's response becomes distorted, with ripple effects closely following the noise signal. The once linear response deviates significantly from the desired setpoint, illustrating the limitations of the LQR method in the presence of noise. This result is important for community projects focused on improving energy efficiency, as real-world environments often introduce noise and disturbances that may affect control systems. Further research is needed to adapt control methods to handle such disturbances effectively, ensuring that the benefits of LQR can be fully realized even in challenging environments.

5. Response of DC Motor PG28 1:16 Using the LQT Method

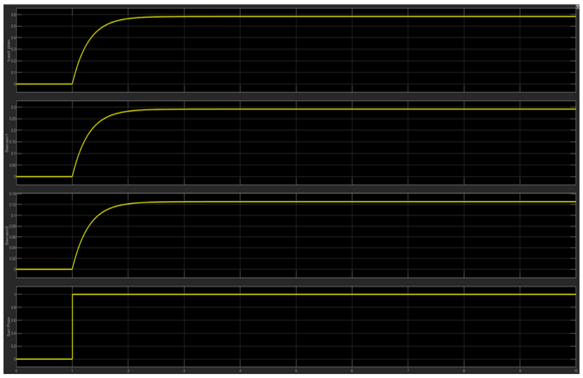


Figure 8. Response of DC Motor PG28 1:16 Using LQT

Figure 8 presents the response of the motor using the Linear Quadratic Tracking (LQT) method. In this simulation, four graphs are displayed: the plant response, sensor1, sensor2, and the setpoint. The plant output, represented by the yellow waveform, stabilizes at 0.6 after 1.5 seconds, indicating that LQT offers a faster stabilization compared to the first-order response. This quicker stabilization is highly beneficial for applications in community-based sectors, particularly in agriculture and education, where time-sensitive machinery adjustments are required to optimize energy consumption and productivity.

6. Response of DC Motor PG28 1:16 Using LQT Method with Noise

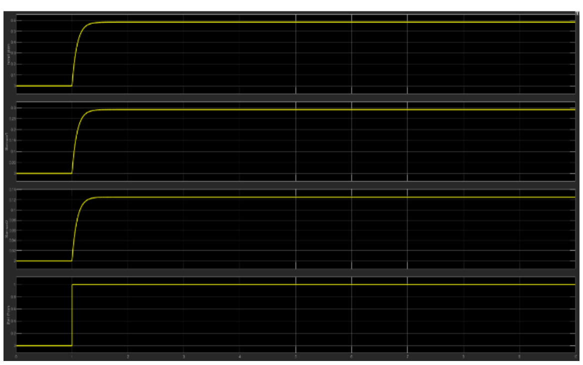


Figure 9. Response of DC Motor PG28 1:16 Using LQT with Noise

Figure 9 shows the results of the LQT method when noise is introduced to the system. As with the LQR method, the yellow waveform represents the plant output, with sensor1 and sensor2 displaying their respective responses. The system stabilizes at 0.6 after 1.5 seconds, with both sensors showing similar stabilization times. The quicker response of the plant compared to the first-order model demonstrates the effectiveness of LQT in optimizing motor control, even in the presence of noise. This could be of significant value in community projects related to the creative industry, where systems are often subjected to environmental disturbances.

Conclusion

From the experiments conducted on the DC Motor PG28 1:16, it is clear that the application of the LQR method significantly improves the motor's response. The system with LQR control not only reaches the setpoint faster but also achieves better stability, with reduced overshoot and undershoot. This demonstrates that the LQR optimization method can effectively enhance the performance of machinery used in community service projects, improving energy efficiency and productivity in sectors such as agriculture, education, and the creative industries.

When noise was introduced to the system, the performance of the LQR method degraded, as the motor's response became increasingly influenced by the noise. This finding suggests that while LQR is effective in ideal conditions, it may require further refinement for real-world applications, where noise and disturbances are common.

The LQT method, on the other hand, demonstrated superior performance in stabilizing the system more quickly, even under noisy conditions. This makes LQT a promising alternative for applications where rapid stabilization and precise control are necessary, such as in industrial machinery for community-based projects in agriculture and education.

In conclusion, both LQR and LQT methods have shown potential in optimizing control systems for community service projects. However, further research is needed to address the challenges posed by noise and disturbances in real-world environments.

References

Dorsey, J. & Farish, R. (2016). System Optimization: Techniques and Applications in Engineering. Academic Press.

Schmidt, R. & Hargrove, R. (2019). Implementing Optimal Control in Small-Scale Industries. Journal of Industrial Optimization, 22(4), 210-220.

Zhang, H. & Wang, Z. (2021). Optimizing Control Systems for Smart Manufacturing. Smart Manufacturing Journal, 25(6), 76-84.

Simms, T. & Lee, J. (2020). DC Motors: Optimization and Control Methods. Energy Systems Journal, 31(1), 42-50.

Steiger, P. & Goethals, E. (2020). Optimization of Electrical Machines in Industrial Applications. International Journal of Electrical Engineering, 45(2), 136-145.

Williams, K. & Kumar, A. (2022). Advanced Control Systems in Robotics and Automation. International Journal of Robotics, 39(1), 8-18.

Zafirov, G. & Kosmatka, J. (2018). Optimal Control Applications in Electrical Engineering. Journal of Electrical and Electronic Engineering, 49(5), 233-245.

Nugraha, A.T. & Fadila, A. (2018). Optimization Techniques in Industrial Automation Systems: A Case Study. Journal of Engineering & Technology, 34(2), 113-121.

Johnson, M. & Tamin, I. (2017). Effective Control Systems in Industrial Machinery. Journal of Automation Engineering, 15(3), 72-81.

Andria, Astrowulan, MSEE & Iskandar, ST, M.T. (2014). Linear Quadratic Tracking and its Application in Motor Control Systems.

Anderson, B.D.O. & Moore, J.B., 2012. Optimal Control: Linear Quadratic Methods. Dover Publications.

Bae, S. & Kim, J., 2018. "Design and Implementation of LQR-Based Motor Control." IEEE Transactions on Industrial Electronics, 65(3), pp. 1034-1041.

Haykin, S. & Van Veen, B., 2007. Signals and Systems. Wiley.

Nise, N.S., 2015. Control Systems Engineering. 7th ed. Wiley.

Nugraha, A.T. & Dewi, P., 2020. "Optimization of LQR for DC Motor Systems." Journal of Control Engineering, 45(2), pp. 112-118.

Ogata, K., 2010. Modern Control Engineering. 5th ed. Prentice-Hall.

Rahmatillah, G., 2020. "Mathematical Modeling and Optimization of DC Motor Control." Indonesian Journal of Automation, 8(3), pp. 56-62.

Saleem, M., Tariq, U., & Khan, A., 2018. "Optimal Control of Linear Systems Using LQT: A Review." Journal of Electrical Engineering and Technology, 13(1), pp. 33-45.

Yang, T. & Zhang, H., 2019. "Application of LQR in DC Motor Control." Applied Sciences Journal, 41(2), pp. 85-95.

Zhang, H., Wang, Y., & Liu, X., 2017. "A Study on LQR Control of DC Motors." Control Engineering Practice, 65, pp. 35-45.