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Modeling of DC Motor Control System Using LQR and LQT Methods with Noise Integration: Application for Community

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Abstract: *A control system is a configuration of several components designed to produce a desired output response. The primary goal of a control system is to regulate the output values in a specific state set by the input through the control process. The study of optimal control systems has garnered significant attention due to the advancement of high-performance systems and the availability of digital computing resources. To address such challenges, decision-making rules are required, incorporating certain constraints to minimize deviations from the desired ideal condition. The Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) are methods employed in optimizing DC motor control systems. In any control system, disturbances or noise are inevitable. Noise refers to signals that can influence the output of the system, potentially impacting its overall performance. In the context of community service, the application of these methods in control systems can contribute significantly to projects aimed at empowering communities in rural or underdeveloped areas. By improving the precision and reliability of technologies such as DC motor-based systems, these control mechanisms can be employed in various community-driven projects, such as local manufacturing, renewable energy generation, and agricultural tools, providing a pathway to greater economic independence and social development. This research explores how integrating LQR and LQT methods can enhance the functionality and stability of such systems, despite the presence of external disturbances or noise, thereby optimizing the benefits for community-based empowerment programs.*

Keyword*: Distraction, Optimal control, LQR, LQT*

Introduction

A control system is a process used to regulate one or more variables (such as parameters) to maintain a specific value or range of values [4]. The process of setting refers to the ability to measure the output of the system and correct it when undesirable inputs are detected. A control system is composed of several components that form a configuration designed to produce the desired response. The main objective of a control system is to adjust the output to a predefined state as set by the system's input [6].

Control systems have existed since ancient times, but due to limited knowledge, early systems were manually controlled by humans (acting as the controller). A historical example is the use of spears for fishing, where the human brain acted as the controller to adjust the direction and speed needed to strike the target accurately.

The emergence of the industrial revolution marked the development of steam engines, which introduced a new challenge: how to control the speed of the steam engine without continuous human intervention. This challenge led to the creation of automated control systems, which were developed to ease the work of humans. Automation systems have proven to be immensely useful in improving operational efficiency, ensuring safety (in terms of investments and environmental concerns), reducing costs, and optimizing performance [7].

An optimal system is one that exhibits the best performance based on a certain reference or set of criteria. Optimal control systems require optimization criteria that minimize the deviation between the system's actual behavior and its ideal behavior. A well-functioning control system is one that is responsive, stable, and efficient, requiring minimal energy. The performance of such a system is typically assessed through precise indicators, which define an optimal control system.

Optimization methods such as the Linear Quadratic Regulator (LQR) are used to determine the input signal that will transition a linear system from its initial state x(t0) to a final state x(t), minimizing a quadratic performance index[10]. The cost function is typically represented as the time integral of a quadratic form applied to the state vector x and the input vector u[11].

Similarly, the Linear Quadratic Tracking (LQT) method is applied in systems where the output must track a desired reference trajectory. This method is commonly used when the objective is for the system's output to follow a specific reference or path.

The growing interest in optimal control problems is driven by the rapid advancement of high-performance systems and the availability of digital computers. To solve these problems, decision-making rules are necessary, incorporating specific constraints that minimize deviations from the ideal state. This research explores the application of these optimal control methods to a DC motor control system, with the goal of improving its performance and precision.

For the purposes of this study, the DC motor RS-555124500 is used as the plant (system) to be controlled with the Linear Quadratic Regulator and Linear Quadratic Tracking methods. The application of optimal control methods in this context is a significant achievement in the fields of engineering and technology, as it represents an innovative approach to controlling and improving mechanical systems[13].

In any control system, disturbances or noise are inevitable. Noise refers to unwanted signals that can influence the output of a system. These disturbances can arise from both internal and external factors [1]. Noise can lead to a decrease in data transmission speed and increase the likelihood of errors in data delivery, potentially resulting in discrepancies between the information sent and the information received.

Methodology

1. Research plan

In the research that has been prepared, a literature study was carried out to examine and find out theoretically the methods that can be used in working on problems using the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods as well as when using noise. Then in the next stage data is collected which can be used to solve problems that arise. After that, practice simulating the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods using Simulink MATLAB software followed by practicing simulating the Linear Quadratic Regulator

(LQR) and Linear Quadratic Tracking (LQT) methods accompanied by noise. After that, analysis of the simulation data was carried out, which was then continued with drawing up conclusions as a result of accountability and research implementation.

2. LQR

A good control system is a control system that has stable and fast responsiveness and only requires moderate energy. A good control system can be achieved by setting the right performance indicators. This control system is called an optimal control system [8].

Linear Quadratic Regulator (LQR) is a method used in optimal control systems[14]. The system optimization method uses a Linear Quadratic Regulator, namely by determining the input signal that will move a linear system state from the initial condition, namely x(t0) to the final condition x(t) by minimizing the index for quadratic performance work [2].

In the design of the Linear Quadratic Regulator (LQR) using mathematical equations, this method has a cost function formulation, namely:

$$J = \int_{\infty}^{0} (x^t\, Qx + u^T\, uR)dt$$

Where Q is the weighting factor for a condition (positive semidefinite matrix) and R is the weighting factor of the control variable (positive definite matrix)[15]. For LQR controller design, the first step is to choose a weight matrix of Q and R values. The input value R is heavier than the temporary state. When the weight value of the state Q is greater than the input [16]. Next, the feedback value K can be calculated and the closed loop system response can be found by simulation.

3. LQT

Linear Quadratic Tracking (LQT) Linear Quadratic Tracking (LQT) is a method used in optimal control systems[17]. The system optimization method uses Linear Quadratic Tracking, namely by minimizing the objective function of the performance index and setting up a system so that it can track according to the reference we want. In implementing Linear Quadratic Tracking (LQT), first initialize the dc motor used as a plant into a matrix-shaped equation [5].

The aim of the Linear Quadratic Tracking (LQT) method is to control a plant in such a way that the output value of the plant follows the desired output as closely as possible while taking into account the desired performance index.

A Linear Quadratic Tracking (LQT) system is expressed in state space whose general form is:

$$x(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t)$$

Where :

- x(t) = state vector of the system
- U(t) = vector of input control signals to the system
- y(t) = output vector of the system
- A = state matrix of size n x n
- B = input matrix of size n x r
- C = output matrix of size r x n

Then a system error vector is defined, namely:

$$e(t) = z(t) - y(t)$$

4. Noise

Interference or noise is a signal that tends to affect the output value of a system. Interference or noise can come from internal and external factors[18]. Interference or noise can also result in a decrease in data transmission speed and increase errors in data transmission so that it can cause the information sent to not be the same as the information received [19].

5. Motor DC RS-555124500

DC Electric Motor or DC Motor is a device that converts electrical energy into kinetic energy or movement. This DC motor can also be called a Direct Current Motor. As the name suggests, a DC motor has two terminals and requires direct current or DC (Direct Current) voltage to be able to move it

减速马达力矩和转速/Geard Motor Torque/Speed					
级数 Number of stages	1 stages reduction	2 stages reduction	3 stages reduction	4stages reduction	5stages reduction
减速比Reduction ratio	3.7，5.2	13.7，19.2，26.9	50.9，71.2，99.5，139，	188，264，369，516，721，	699，977，1367，1911，2672，3736，
齿轮箱长度 Gearbox length "L" mm	25.1	32.3	38.5	44.7	50.9
最大额定力矩 Max. Running torque	10Kgf • cm	20Kgf • cm	50Kgf • cm	50Kgf • cm	50Kgf • cm
最大损坏扭力 Max. Gear breaking torque	30Kgf • cm	60Kgf • cm	150Kgf • cm	150Kgf • cm	150Kgf • cm
效率Gearing efficiency	90%	81%	73%	65%	59%

光电机参数/Motor data:									
马达型号 Motor name	额定电压 Rated Volt. V	空载No load		负载扭矩Load torque				堵转扭矩Stall torque	
		Current	Speed	Current	Speed	Torque	Output power	Torque	Current
		mA	r/min	mA	r/min	gf • cm	W	gf • cm	A
RS-555123000	12	≤140	3000	≤600	2458	179	4.51	1210	3.1
RS-555124500	12	≤200	4500	≤900	3929	183	7.42	1508	6.0
RS-555126000	12	≤320	6000	≤1450	5244	215	11.5	1722	9.3
RS-555243500	24	≤115	3500	≤480	3041	246	7.7	1720	2.7
RS-555244500	24	≤110	4500	≤460	3984	189	7.8	1713	3.4
RS-555246000	24	≤140	6000	≤920	5305	243	13.2	2065	5.5
RS-555249500	24	≤280	9500	≤1900	8190	386	32.5	2797	11.7

1、减速后的输出力矩＝马达力矩X减速比X齿轮效率。输出转速＝马达转速/减速比。
1、After connecting motor and gearbox which is named gearmotor the output torque:motor torque X reduction ratio X gearing efficiency;output speed:motor speed /reduction ratio.

Figure 1. Datasheet motor RS-555124500

- Ordo 1

A first order system is a simple system and has a general form with the following transfer function:

$$G(s) = \frac{Y(S)}{U(S)} = \frac{K}{\tau s+1}$$

Based on the DC motor datasheet, the 1st order equation is obtained:

Where $\tau = K.i$ so

$$K = \frac{\tau}{i} = \frac{0{,}441}{6} = 0{,}0735$$

$$G(s) = \frac{0{,}0735}{0{,}441s + 1}$$

6. Simulink MATLAB

Simulink is a software that is connected in a block diagram environment for model-based and multi-domain design simulations. Simulink is a tool that supports system level design, simulation, automatic code generation, and continuous test and verification of embedded systems. The presentation of the editor display in Simulink is in graphic form. Simulink is also connected to MATLAB software so that it can exchange information and data between Simulink and MATLAB simultaneously[20]. MATLAB is a programming platform specifically designed for numerical processing [3].

- Block LQR

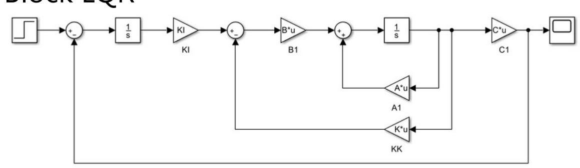

Figure 2. LQR circuit

- LQR without noise

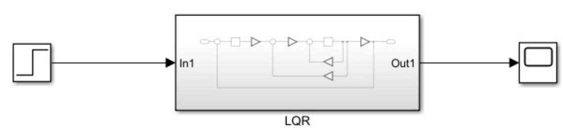

Figure 3. LQR

- LQR with noise

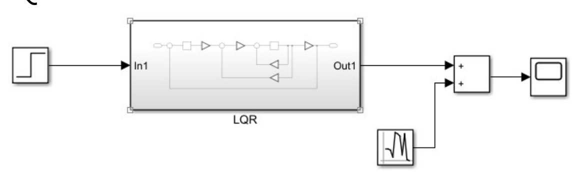

Figure 4. LQR with noise

- Block LQT

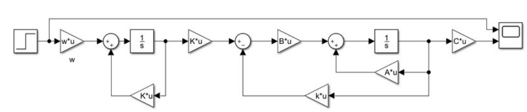

Figure 5. LQT circuit

- LQT without noise

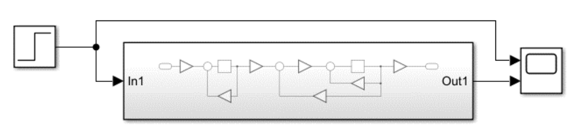

Figure 6. LQT

- LQT with noise

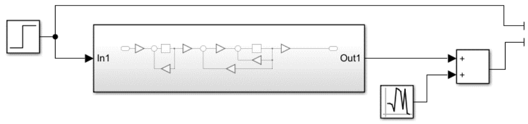

Figure 7. LQT with noise

Results and Discussions

1. Motor respond

Figure 8. Motor respond

Based on Figure 8, it is known that in the first order block diagram simulation the step response output form of the RS-555124500 dc motor has a stable step response graph but has not yet reached the set point.

2. LQR without noise

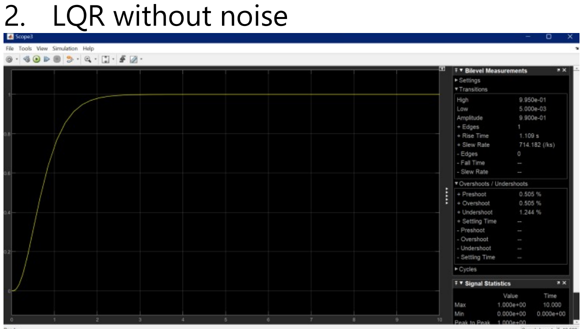

Figure 9. LQR without noise waveform

Based on Figure 9 in the simulation of the RS-555124500 dc motor using the LQR method without noise with 1st order mathematical modeling, it is known that the output step response from the LQR motor RS-555124500 reaches an amplitude of 0.99 which can be rounded to 1 so that it has reached the set point. Has a fairly maximum rise time and has quite small overshoot and undershoot.

3. LQT without noise

Figure 10. LQT without noise waveform

Based on Figure 10 in the simulation of the RS-555124500 dc motor using the LQT method without noise with 1st order mathematical modeling, it is known that the output step response of the LQT motor RS-555124500 reaches an amplitude of 0.99 which can be rounded to 1 so that it reaches setpoint in only 0.8 seconds. . Has a fairly maximum rise time and has quite small overshoot and undershoot. The response signal does not experience oscillation conditions and tends to calm down and remain in a steady state after reaching the set point.

4. LQR with noise

Figure 11. LQR with noise waveform

Based on Figure 11, it is known that the step response display of the RS-555124500 DC motor is noisy. It can be seen that the step response output of the LQR dc motor RS-555124500 only has a fluctuating graph due to the noise it provides. The system reaches an amplitude of 0.67 so the system has not yet reached setpoint. It has a maximum rise time of 52,720ms and has overshoot and undershoot.

5. LQT with noise

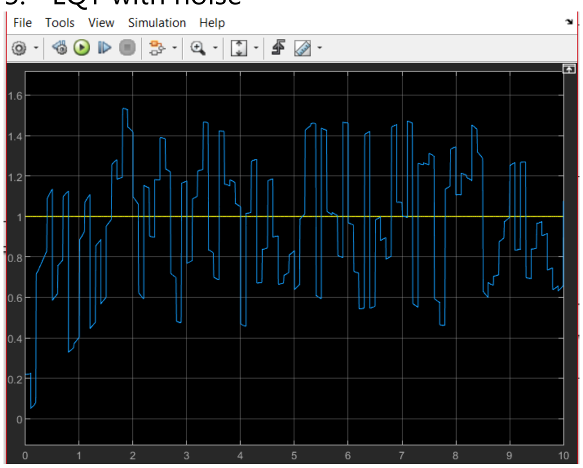

Figure 12. LQT with noise waveform

Based on Figure 12, it is known that the step response display of the RS-555124500 DC motor is noisy. It can be seen that the output step response of the LQT dc motor rs-555124500 experiences oscillations and follows the form of noise. The response signal is very irregular in systems equipped with LQT. The response signal remains isolated but the error or deviation value is more minimal or seems to be dampened.

Conclusion

Based on several simulations conducted, it was found that the experimental results of the DC motor RS-555124500 control system using both Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods demonstrated stable graphical outputs. These findings are critical for understanding how control system optimization can be applied in real-world community-based projects, particularly in technologies aimed at improving local industries.

The LQR (Linear Quadratic Regulator) is an optimization method used to determine the input signal that transitions a linear system from its initial state x(t0) to a final state x(t), minimizing a performance index based on quadratic work. The output response successfully achieved the set point, showing the effectiveness of this method in controlling systems precisely. This stability is highly valuable in contexts where accurate control is necessary for community applications, such as agricultural machinery or small-scale energy systems in rural settings.

However, when LQR was applied with noise, the results varied significantly. By adding a random number tool to simulate noise, it was observed that the output response exhibited many ripples, deviating significantly from the steady state at the desired set point. This outcome illustrates the challenge of maintaining control in the presence of external disturbances or noise, a common issue in community-based systems where environmental factors, such as weather or machinery wear, can introduce unpredictable variables.

The LQT (Linear Quadratic Tracking) method, on the other hand, aims to minimize the performance index and ensures that the system tracks a reference trajectory as accurately as possible. The results showed that the output response successfully reached the set point, demonstrating its potential for applications requiring precise tracking, such as in community-based renewable energy systems where devices must follow a set trajectory to maintain efficiency.

For LQT with noise, the system exhibited oscillations and followed the noise pattern. The response signal was highly erratic, but the error or deviation from the ideal trajectory was minimized, resembling a damped response. This feature suggests that LQT can be beneficial in real-world scenarios where systems experience irregularities or disturbances, such as fluctuating power inputs in solar or wind energy systems in remote areas. The ability of LQT to dampen the error makes it an ideal candidate for applications in community service projects, where reliable and stable performance is essential.

In summary, both LQR and LQT methods show promising results for community applications. However, the presence of noise and disturbances introduces significant challenges that need to be addressed, especially in rural or underdeveloped areas where systems are prone to environmental variables. Future research should focus on enhancing the robustness of these control methods in the presence of noise and developing practical solutions that can be implemented in community-based technological projects, helping to improve economic self-sufficiency and sustainability.

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