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Optimization of Application Control Using LQR and LQT Approaches: A Study on Community-Based Development Programs

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Abstract: *The rapid advancements in technology today have led to a growing reliance on automated tools over manual human labor. One of the widely used actuators across various fields is the DC Motor. This paper focuses on integrating tools with Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) approaches. LQR is an optimal control method applied to state-space-based systems. The LQR controller requires the definition of two parameters, namely the Q and R weighting matrices, which must be carefully determined to achieve optimal control actions as desired. Unlike the Proportional-Integral-Derivative (PID) controller, which features systematic tuning methods like Ziegler-Nichols and Cohen-Coon, the LQR controller lacks a dedicated systematic tuning methodology for determining the Q and R weighting matrices. The implementation of these approaches in this study aims to produce more efficient and effective outcomes, particularly in the context of community-based development programs. By optimizing the control systems used in community projects, this research contributes to enhancing the reliability and sustainability of technological solutions applied to improve societal well-being.*

Keyword: *linear quadratic regulator, Linear Quadratic Tracking, optimum*

Introduction

The rapid advancements in technology over recent decades have significantly transformed the way humans work, with a growing reliance on automated tools over manual labor. This trend reflects the increasing demand for higher efficiency and reduced dependence on time- and effort-intensive processes. Among the critical components in various automation systems is the DC motor, which is widely employed across applications ranging from industrial systems to robotics and household devices. In this context, effective control of DC motors is essential to ensure optimal performance, system stability, and efficiency[1][2].

The adoption of optimal control approaches, such as Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT), offers promising solutions for enhancing the performance of state-space-based systems[3][4]. LQR, in particular, is an optimal control method designed to produce efficient control actions by minimizing a cost function defined by two primary parameters: the Q and R weighting matrices[5]. The appropriate selection of these Q and R matrices is critical to the successful implementation of LQR, making their determination a central challenge[6][7].

Unlike the Proportional-Integral-Derivative (PID) controller, which benefits from systematic tuning methods like Ziegler-Nichols and Cohen-Coon, LQR lacks a standardized methodology for tuning its parameters[8]. This absence of a systematic approach often presents a barrier to the practical application of LQR in real-world systems, especially for tasks requiring high precision. Consequently, developing a more structured methodology for defining the Q and R matrices has become a significant focus in optimal control research[9].

This study focuses on implementing LQR and LQT approaches in the development of community-based programs. These methods aim to produce more efficient and effective control systems, ultimately supporting the sustainability of technological solutions within societal contexts. By optimizing control systems, this research seeks to enhance the reliability and impact of technology applications designed to improve societal well-being[10][12].

The contribution of this study extends beyond technical aspects, addressing the reliability and sustainability of community-focused development initiatives. By integrating advanced control approaches, this research aspires to serve as a reference for developing optimal control systems tailored to modern societal needs, reinforcing the role of technology in fostering social progress.

Methodology

1. LQR and LQT

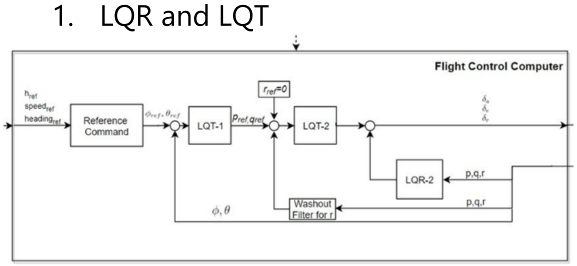

Figure 1.LQR and ;LQT controller

Linear Quadratic Regulator (LQR) is an optimal control method designed to achieve the best possible outcomes while considering the conditions and constraints of a given system. In optimal control systems, the term "optimal" often refers to minimizing certain factors, such as resource consumption [11], time, and errors. Generally, optimal control is employed to select plant inputs u that minimize a specified performance index[13].

Linear Quadratic Tracker (LQT), on the other hand, is a linear control system designed to ensure that the system's output follows a desired reference or trajectory[14]. These methodologies, LQR and LQT, are particularly valuable in community-based development programs, where resource efficiency and precision in achieving objectives are critical. For instance, optimizing energy use in small-scale manufacturing equipment or ensuring precise control in irrigation systems for agricultural communities aligns with sustainable and impactful community service initiatives.

By integrating LQR and LQT within the framework of community service, this study seeks to enhance the effectiveness and sustainability of solutions tailored to the needs of specific populations, thereby contributing to long-term social and economic development[15].

- LQR

Linear Quadratic Regulator LQR is an optimal control which means the best results that can be achieved by paying attention to the conditions and constraints of a system[16][17]. In optimal control systems, the term optimal often refers to minimum, for example minimizing fuel (input), time, and error. Optimal control is generally used to select the input plant u with the minimum performance index. In a system, the performance index is selected according to the part to be optimized. The general form of the state equation of a linear system is shown by Equation:

X=Ax+Bu
Y=Cx

The performance index of minimum energy (cost function/quadratic function) is shown by Eq

$$\int J = \frac{1}{} \quad (x^T Q + u^T R u)\ dt$$

The regulator equation can be solved by solving the allgebraic Riccati equation according to Eq

$$A^T P + PA - PBR^{-1} B^T P + Q = 0$$

$$-K = R^{-1} B^T P$$

$$u = -Kx$$

- LQT

LQT is a linear regulation system where the system output follows the desired reference (trajectory)[18]. A system has a state equation and an error vector such as Equation The performance index is defined in Eq

$$e = z - y$$

$$J = \frac{1}{2} e'(t_f) F(t_f) e(t_f) + \frac{1}{2} \int_{t_0}^{t_f} \left[e' Q e + u' R u \right] dt$$

After obtaining the mathematical model of the system in state-space form, the solution matrix for the differential Riccati equation can be obtained with Equation for the infinite-time case.

$$0 = -PA - A' P + PBR^{-1} B' P + C' QC$$

The Q and R matrices can be assumed to be in accordance with the desired performance of the system. After obtaining the Riccati equation, the nonhomogeneous vector differential equation can be searched using Eq

$$g = -[A - BR^{-1} B' P]' g - C' Qz$$

After getting the matrix P which is a symmetric positive definite matrix and g, the feedback gain value K can be found using the equation

$$K = R^{-1} B' P$$

In the control field, GA can be used to improve system performance. One of them is the Linear Quadratic Tracking (LQT) method. The aim of the LQT method is to obtain optimal control actions that minimize the performance index and instruct the plant to carry out tracking according to a predetermined model (trajectory)[20]. To get maximum control action, it depends on the value of Q and R. The Q and R values are obtained by manual turning (Try and error).

The trial and error tuning method often produces suboptimal control results. To get a combination of Q and R values, a tuning method using GA is used [19]. After obtaining the optimal Q and R values, the optimal feedback gain value will be obtained so that optimal design results are obtained.

2. Motor DC

Electric motors are electromagnetic devices that convert electrical energy into mechanical energy. This mechanical energy is utilized in various applications, such as rotating pump impellers, fans, or blowers, driving compressors, lifting materials, and more. Electric motors are commonly used both in households—such as for mixers, electric drills, and fans—and in industrial settings. Due to their extensive use, electric motors are often referred to as the "workhorses" of the industry, as it is estimated that motors account for approximately 70% of the total electrical load in industrial operations.

In the context of community-based development programs, electric motors can play a pivotal role in advancing small-scale industries and empowering local economies. For instance, optimizing the efficiency and functionality of electric motors in agricultural processing equipment or local manufacturing systems can significantly reduce operational costs and energy consumption. Such improvements not only enhance the productivity of community projects but also align with sustainable development goals by promoting energy efficiency and reducing environmental impact.

This study, which integrates LQR and LQT control strategies for motor optimization, seeks to address these critical issues. By applying advanced control systems, it aims to maximize the effectiveness of electric motor applications, particularly in community-driven initiatives, thereby fostering technological empowerment and improving the quality of life within these communities.

- Method

The quadcopter mathematical model equations are obtained from kinematics and dynamics analysis

$$\ddot{X} = (\sin\psi\sin\theta + \cos\psi\sin\theta\cos\phi)\frac{U_1}{m}$$

$$\ddot{Y} = (-\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi)\frac{U_1}{m}$$

$$\ddot{Z} = -g + (\cos\theta\cos\phi)\frac{U_1}{m}$$

$$\dot{p} = \frac{I_{XX} - I_{YY}}{I_{XX}} qr - \frac{J_{TP}}{I_{XX}} q\Omega + \frac{U_2}{I_{XX}}$$

$$\dot{q} = \frac{I_{ZZ} - I_{XX}}{I_{YY}} pr + \frac{J_{TP}}{I_{YY}} p\Omega + \frac{U_3}{I_{YY}}$$

$$\dot{r} = \frac{I_{XX} - I_{YY}}{I_{ZZ}} pq + \frac{U_4}{I_{ZZ}}$$

The control signal (torque) used to perform thrust force, roll, pitch and yaw angle movements is defined as the sum of the squares of each motor. The relationship between each motor speed to produce a control signal (torque) is in Eq

$$U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2)$$

$$U_2 = l\,b(-\Omega_2^2 + \Omega_4^2)$$

$$U_3 = l\,b(-\Omega_1^2 + \Omega_3^2)$$

$$U_4 = d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2)$$

$$\Omega = -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4$$

- Variable motor dc

Table 1.Motor dc parameter

Parameter	Value	IS
Massa *quadcopter* (*m*)	1,26	kg
***Seqment quadcopter* (*l*)**	0,206	Meter
Gravity (*g*)	9,81	N/m^2
Konstanta *Thrust*	1,6898 x10^{-5}	N s^2
Konstanta *Drag*	4,19 x 10^{-6}	Nms^2

In the equation there are variables from the mathematical model for the rotational motion of the quadcopter that are not yet known. In this study, parametric identification was used with quadcopter flight data

$$\dot{p} = a_1\, qr + b_1\, q\Omega + c_1 U_2$$

$$\dot{q} = a_2\, pr + b_2\, p\Omega + c_2 U_3$$

$$\dot{r} = a_3\, pq + b_3 U_4$$

From the flight data, the quadcopter mathematical model is obtained in Eq

$$\dot{p} = -0{,}5495qr - 0{,}0017q\Omega + 0{,}2052U_2$$
$$\dot{q} = 0{,}16775pr - 0{,}0094p\Omega + 2{,}955U_3$$
$$\dot{r} = -2{,}0257pq + 0{,}0594U_4$$

In this research, rotational motion design uses LQR. The first step is to define the linear relationship between variables. This linear relationship is shown in Eq

$$\dot{\phi} = p\ ,\ \ddot{\phi} = \dot{p}$$
$$\dot{\theta} = q\ ,\ \ddot{\theta} = \dot{q}$$
$$\dot{\psi} = r\ ,\ \ddot{\psi} = \dot{r}$$

To create a state space from LQR roll angle control:

$$\ddot{\phi} = c_1 U_2 + a_1 qr + b_1 q\Omega$$
$$\ddot{\phi} = c_1\left(U_2 + \frac{1}{c_1}(a_1 qr + b_1 q\Omega)\right)$$
$$U_2^* = U_2 + \frac{1}{c_1}(a_1 qr + b_1 q\Omega)$$
$$\ddot{\phi} = c_1 U_2^*$$
$$\begin{bmatrix}\dot{\phi}\\ \ddot{\phi}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}\phi\\ \dot{\phi}\end{bmatrix} + \begin{bmatrix}0\\ c_1\end{bmatrix}U_2^*$$
$$Y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\phi\\ \dot{\phi}\end{bmatrix}$$

As for the pitch angle equation:

$$\ddot{\theta} = c_2 U_3 + a_2 pr + b_2 p\Omega$$
$$\ddot{\theta} = c_2\left(U_3 + \frac{1}{c_2}(a_2 pr + b_2 p\Omega)\right)$$
$$U_3^* = U_3 + \frac{1}{c_2}(a_2 pr + b_2 p\Omega)$$
$$\ddot{\theta} = c_2 U_3^*$$
$$\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\end{bmatrix} + \begin{bmatrix}0\\ c_2\end{bmatrix}U_3^*$$
$$Y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\end{bmatrix}$$

For designing yaw angles

$$\ddot{\psi} = b_3 U_4 + a_3 pq$$
$$\ddot{\psi} = b_3\left(U_4 + \frac{1}{b_3}(a_3 pq)\right)$$
$$U_4^* = U_4 + \frac{1}{b_3}(a_3 pq)$$
$$\ddot{\psi} = b_3 U_4^*$$
$$\begin{bmatrix}\dot{\psi}\\ \ddot{\psi}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}\psi\\ \dot{\psi}\end{bmatrix} + \begin{bmatrix}0\\ b_3\end{bmatrix}U_4^*$$

To get gain feedback from LQR, manual tuning (try and error) is used.

Table 2. Value Q and R

No	Parameter	Value	K
1	Q *Roll*	$\begin{bmatrix}1000 & 0\\ 0 & 1\end{bmatrix}$	$[10^4 \quad 0.044]$
	R *Roll*	0.00001	
2	Q *Pitch*	$\begin{bmatrix}1000 & 0\\ 0 & 4\end{bmatrix}$	[100 10.3764]
	R *Pitch*	0.1	
3	Q *Yaw*	$\begin{bmatrix}1000 & 0\\ 0 & 4\end{bmatrix}$	$[3.162 \times 10^3 \quad 0.3827]$
	R *Yaw*	0.00001	

To eliminate nonlinear effects from the model, modifications are used

$$U_x^* = (\sin\theta\cos\phi)\frac{U_1}{m}$$
$$\ddot{X} = U_x^*$$
$$\begin{bmatrix}\dot{X}\\ \ddot{X}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}X\\ \dot{X}\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix}U_x^*$$
$$Y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}X\\ \dot{X}\end{bmatrix}$$

The LQT control signal is θref, so the Ux* control signal is converted to θ

$$\sin\theta = \frac{mU_x^*}{U_1\cos\phi}$$
$$\theta = arc\sin\left(\frac{mU_x^*}{U_1\cos\phi}\right)$$

In controlling translational motion, the Y axis is the same as the X axis

$$\ddot{Y} = (-\sin\phi)\frac{U_1}{m}$$

To eliminate nonlinear effects from the model, modifications are used

$$U_y^* = (-\sin\phi)\frac{U_1}{1.26}$$
$$\ddot{Y} = U_y^*$$
$$\begin{bmatrix}\dot{Y}\\ \ddot{Y}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}Y\\ \dot{Y}\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix}U_y^*$$
$$Y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}Y\\ \dot{Y}\end{bmatrix}$$

The LQT control signal is ϕref, so the control signal Uy* is converted to ϕ

$$\sin\phi = \frac{(-1.26)U_y^*}{U_1}$$
$$\phi = arc\sin\left(\frac{(-1.26)U_y^*}{U_1}\right)$$

$$\ddot{Z} = -g + (\cos\theta\cos\phi)\frac{U_1}{m}$$
$$U_1^* = -g + (\cos\theta\cos\phi)\frac{U_1}{m}$$
$$\ddot{Z} = U_1^*$$
$$\begin{bmatrix}\dot{Z}\\ \ddot{Z}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}Z\\ \dot{Z}\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix}U_1^*$$
$$Y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}Z\\ \dot{Z}\end{bmatrix}$$

In this study, controlling translational motion with GA tuning is limited to controlling translational motion on the X and Y axes. For the Z axis, the trial and error tuning method is used in Table 3.

Table 3. Value Q and R

No	Parameter	Value
1	Qz	1000
2	Rz	0.0001

Results and Discussions

The results of the discussion are shown below

Table 3. Respond variation Q in LQR Roll Angle

Q	K	τ	t_s	t_r
$\begin{bmatrix} 10 & 0 \\ 0 & 1 \end{bmatrix}$	[1000 331,281]	0,332	0,996	0,978
$\begin{bmatrix} 100 & 0 \\ 0 & 1 \end{bmatrix}$	[3,162 x10^3 0.362]	0,110	0,331	0,325
$\begin{bmatrix} 1000 & 0 \\ 0 & 1 \end{bmatrix}$	[10^4 0,044]	0,048	0,146	0,143
$\begin{bmatrix} 1000 & 0 \\ 0 & 4 \end{bmatrix}$	[10^4 0,071]	0,073	0,219	0,214
$\begin{bmatrix} 800 & 0 \\ 0 & 4 \end{bmatrix}$	[9,94 x 10^3 0,698]	0,080	0,241	0,237
$\begin{bmatrix} 500 & 0 \\ 0 & 4 \end{bmatrix}$	[7,07 x 10^3 0,685]	0,099	0,2982	0,2927

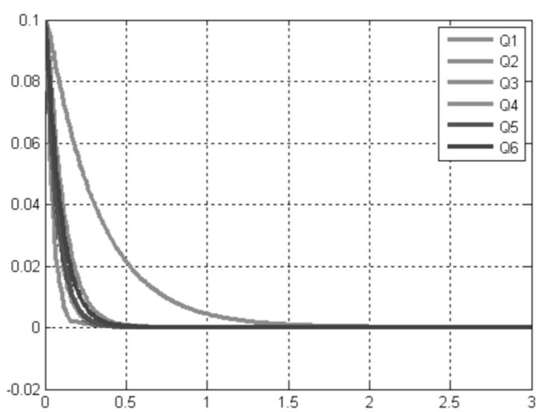

Figure 2. Graph respond variaton Q control Roll Angle

Table 4. Respond variation Q in LQR Pitch Angle

Q	K	τ	t_s	t_r
$\begin{bmatrix} 10 & 0 \\ 0 & 1 \end{bmatrix}$	[10 4,095]	0.428	1.284	1.26
$\begin{bmatrix} 100 & 0 \\ 0 & 1 \end{bmatrix}$	[31,623 5,604]	0.2006	0.602	0.591
$\begin{bmatrix} 1000 & 0 \\ 0 & 1 \end{bmatrix}$	[100 8,813]	0.1055	0.3165	0.311
$\begin{bmatrix} 1000 & 0 \\ 0 & 4 \end{bmatrix}$	[100 10,3764]	0.1157	0.3471	0.341
$\begin{bmatrix} 800 & 0 \\ 0 & 4 \end{bmatrix}$	[89,443 10,026]	0,124	0,372	0,365
$\begin{bmatrix} 500 & 0 \\ 0 & 4 \end{bmatrix}$	[70,711 9,373]	0,1442	0,4326	0,425

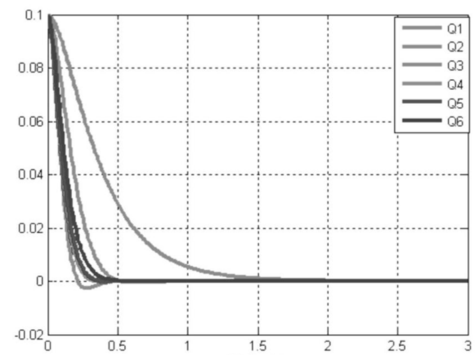

Figure 3. Graph respond variaton Q control Pitch Angle

Conclusion

Linear Quadratic Regulator (LQR) is an optimization method used to determine the input signal that guides a linear system from its initial condition x(t0) to a desired state x(t), while minimizing a performance index, specifically a quadratic performance index. Both LQR and Linear Quadratic Tracker (LQT) approaches are highly valuable and effective in their applications. Their ability to optimize control systems and achieve precise, efficient performance makes them indispensable tools in various fields, ranging from industrial automation to community-based technological solutions. The significant contribution of these methods lies not only in their theoretical framework but also in their practical impact, offering more reliable and sustainable outcomes in real-world implementations.

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