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Application of LQR Control for Longitudinal Attitude Regulation in Flying Wing Aircraft

Anggara Trisna Nugraha[1], Rizki Abdi Pradana[2], Muhammad Jafar Shiddiq[3]
[1,2] Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya
3 Automation Engineering, Shipbuilding Institute of Polytechnic Surabaya
[1] anggaranugraha@ppns.ac.id

Abstract

The development of Unmanned Aerial Vehicles (UAVs) has garnered significant attention from various sectors, especially in the context of aerospace engineering, due to their versatility and increasing applications. UAVs have found widespread use in missions such as regional surveillance, military reconnaissance, and mapping tasks. However, the relatively small size of these aircraft makes them highly susceptible to environmental disturbances, particularly wind, which can lead to instability and potential stalling, thereby compromising mission success. This issue emphasizes the need for an effective and responsive control system capable of adjusting the UAV's motion to prevent such instability.In this research, the Linear Quadratic Regulator (LQR) control method is implemented to manage the roll angle of a flying wing UAV, ensuring the maintenance of its longitudinal stability. The study demonstrates that the LQR control method effectively regulates the roll angle, allowing the aircraft to maintain stable flight under various conditions. Experimental results reveal that when the roll angle is disturbed, the UAV experiences a brief overshoot of 4.28°, but quickly returns to its stable state. The system exhibits a rise time of 0.7 seconds, a settling time of 1.3 seconds, and a steady-state error of 1.37°, indicating the effectiveness of the LQR control in maintaining longitudinal stability despite external disturbances.

Keywords: Unnamed Aerial Vehicle, Longitudinal, LQR, Steady State Error

1. Introduction

Recent technological advancements have significantly impacted various sectors, especially in the domain of Unmanned Aerial Vehicles (UAVs), where they have gained substantial attention from both research communities and industries (Sheila et al., 2024). UAVs, owing to their portable systems and compact designs, have become a versatile tool for a variety of applications, including military reconnaissance, environmental monitoring, and regional mapping (Dermawan et al., 2023). These vehicles, often referred to as Unmanned Aircraft Systems (UAS), are typically operated remotely or autonomously, with no onboard pilot, which makes them particularly useful for missions that require flexibility and precision in difficult or hazardous environments (Satrianata et al., 2023).

UAVs, particularly the flying wing configuration, have become an important class of aircraft due to their unique aerodynamic properties (Ainudin et al., 2022). The flying wing design, characterized by a triangular shape and lack of tail (tailless configuration), offers several advantages, including reduced weight, improved glide performance, and greater maneuverability (Nugraha et al., 2023). These UAVs are equipped with elevons for controlling pitch and roll movements, and are typically powered by brushless motors for propulsion. Due to their efficient gliding ability, flying wing UAVs can cover vast areas effectively, making them ideal for long-duration flights while carrying significant payloads such as cameras and sensors (Wibowo & Nugraha, 2023).

Despite these advantages, the small size of UAVs like the flying wing makes them highly susceptible to environmental disturbances, particularly wind. These disturbances can lead to loss of stability, potentially causing the aircraft to stall and compromise mission objectives (Agna, Sobhita, & Nugraha, 2023). A stall occurs when the angle of attack exceeds the critical limit, often greater than 25 degrees for UAVs, resulting in a sudden loss of lift and uncontrolled descent. This scenario, if left unaddressed, can lead to significant mission failure. In manual flight control, these issues can be corrected relatively easily by the operator, but in autopilot mode, such disturbances become a critical concern. Therefore, a robust control system is essential to maintain the UAV's stability and prevent stalling, particularly in autonomous flight operations.

The control of UAV attitude is critical for ensuring stable flight, and the longitudinal attitude, influenced by the roll angle, plays a key role in maintaining overall stability. The rolling motion is typically controlled by adjusting the ailerons on both wings, moving them in opposite directions to achieve the desired roll (Nugraha & Sugianto, n.d.). The ability to control this roll angle effectively is crucial to maintaining the aircraft’s stability, especially when operating autonomously.

In recent research, several control methods have been proposed to address the challenges of maintaining stable longitudinal attitude. One common approach is the use of the Proportional-Integral-Derivative (PID) controller, which has been successfully applied to control the roll angle of UAVs. However, PID controllers often suffer from large overshoots and long settling times, which are undesirable in high-performance applications. Erwin Irmawan and colleagues explored a combination of Adaptive Neuro Fuzzy Inference System

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(ANFIS) and PID control to enhance response time, achieving better stability and faster convergence, although the system still exhibited significant overshoot.

Given the challenges faced by traditional control methods, a more advanced control strategy is required for achieving precise and rapid stabilization. One such approach is the Linear Quadratic Regulator (LQR) control method, which is known for its effectiveness in handling systems that require both fast and stable performance. The LQR method has been successfully applied in various aerospace applications, including quadcopters, to maintain stable flight attitude despite external disturbances (Almunawar et al., 2024). The LQR controller works by optimizing a cost function that balances state errors and control effort, providing an optimal solution for stabilizing the UAV quickly and accurately.

This study aims to apply the LQR control method to the longitudinal attitude control of a flying wing UAV. The LQR method will be used to regulate the roll angle of the UAV to ensure stable flight and prevent stalling. The use of this method is expected to improve the performance of the UAV, achieving fast stabilization times with minimal overshoot and steady-state error, making it a valuable tool for autonomous UAV operations.

LQR controllers require that the states of the system, such as position, velocity, and angles, be available for measurement or estimation (Saputra et al., 2024). In cases where some states cannot be directly measured, an observer or estimator can be used to approximate these states based on the available outputs and the plant model. This feature makes LQR a powerful tool for controlling UAVs in environments where real-time measurements are critical.

2. Material and methods

2.1. LQR

The Linear Quadratic Regulator (LQR) is a state-space-based control method that employs linear system models and linear controller formulations. This control strategy uses a state feedback law to ensure optimal performance (Argentim et al., 2013). In the LQR framework, the system dynamics are modeled using linear state equations, and the feedback control law is designed to minimize a specific cost function. The general form of the system and feedback law is represented in the following set of equations:

$$x=Ax+Bu$$
$$u=Cx$$
$$u=-Kx$$

Where x represents the state vector, u is the control input, A , B, and $C$are system matrices, and K is the feedback gain matrix that must be optimized.

The LQR control method operates by determining two critical parameters: the weighting matrices Q and R, which directly influence the optimal feedback gain K (Sam et al., 2000). These matrices define the relative importance of minimizing the state error and the control effort. The tuning of matrices Q and R is crucial for achieving the desired system response. The process of selecting appropriate values for these matrices is iterative, beginning with an initial value of one and gradually adjusting based on the system's response to disturbances and control inputs. This stepwise approach ensures that the system stabilizes effectively, providing both quick response times and minimal overshoot.

The optimization of the Q and R matrices is a vital aspect of the LQR design process, as it directly impacts the system's ability to respond to dynamic changes and maintain stability under varying conditions (Kumar & Jerome, 2013). Fine-tuning these parameters is essential for improving the robustness of the controller, especially in real-world applications where environmental disturbances and system uncertainties can significantly affect performance.

The strength of the LQR method lies in its ability to balance control effort and state error, providing a systematic approach to achieving optimal control for systems like Unmanned Aerial Vehicles (UAVs). For UAVs, particularly those with complex configurations like the flying wing, this control method ensures that the aircraft maintains its desired longitudinal stability, especially in the presence of external disturbances such as wind. Thus, the LQR approach offers a powerful solution for enhancing the stability and performance of UAV systems, making it highly suitable for long-duration flights and critical missions where quick recovery from disturbances is essential.

2.2. Unmanned Aerial Vehicle (UAV)

An Unmanned Aerial Vehicle (UAV) is a type of aerial system capable of flying over long distances, controlled remotely by a pilot or autonomously via an embedded control system. UAVs can operate without an onboard pilot, with their movements directed by external control signals or pre-programmed instructions within the system. Among the various types of UAVs, the flying wing design stands out due to its unique aerodynamic structure (Mohsan et al., 2022). The flying wing, characterized by its triangular shape, is equipped with elevons that control its motion. This design contributes to its excellent gliding capability, enabling the UAV to cover long distances while carrying payloads effectively.

When in flight, the UAV experiences two simultaneous types of motion: translational and rotational. Translational motion refers to the linear displacement along the three principal axes, while rotational motion involves the aircraft's attitude changes around these axes (Liu et al., 2014). The dynamic model of the flying wing's motion is illustrated in Figure 1, which provides a comprehensive depiction of how these motions interact during flight.

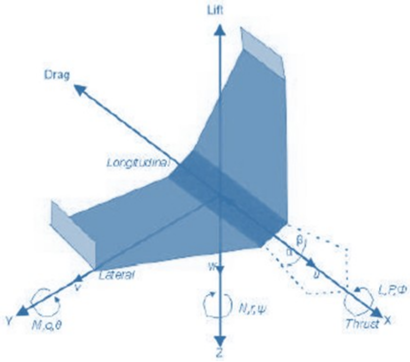

Figure 1. Dynamic model of flying wing

The translational motion of the UAV occurs along three primary axes: vertical, horizontal, and longitudinal. The determination of translational movement is governed by Newton-Euler's equations, which are derived from Newton's second law of motion. These laws form the foundation of the mathematical modeling of UAV dynamics, especially for controlling the aircraft's stability and ensuring accurate navigation during autonomous missions.

In this context, the flying wing UAV is susceptible to disturbances, such as wind or changes in flight conditions, which can affect its stability and control. Therefore, advanced control strategies like the Linear Quadratic Regulator (LQR) are essential in mitigating such disturbances and maintaining the UAV's longitudinal stability, which is critical for ensuring mission success and operational efficiency (Otto et al., 2018). The effectiveness of LQR control is crucial in enhancing the UAV's ability to return to its equilibrium state, especially after disturbances such as roll angle changes or external wind gusts.

2.3. Unmanned Aerial Vehicle (UAV)

The implementation of the system involved the development of a flying wing UAV, constructed from polyfoam material, with a wingspan of approximately 120 cm and a weight of around 1 kg. This design integrates various electronic components essential for flight control and operation. The aircraft is equipped with actuators, including servo motors installed on both the left and right wings, as well as a brushless motor with a propeller mounted at the rear of the aircraft (Nst et al., 2018). This configuration allows the UAV to perform efficient and stable flight maneuvers. A visual representation of the UAV is shown in Figure 2.

Figure 2. Flying Wing UAV

The electronic system implemented within the UAV is shown in Figure 2. The system comprises several key components, including an accelerometer and gyroscope, which function as sensors for measuring roll and pitch angles. These sensors provide crucial data for monitoring the aircraft's attitude and stability. The UAV is also equipped with a telemetry module, which facilitates the transmission and reception of data between the aircraft and the ground control station. Additionally, a remote receiver is installed to allow for manual flight control input from the operator, providing flexibility in flight mode operation.

The core of the system's control processing is based on a Tensy microcontroller. This microcontroller is responsible for processing sensor data and executing the software embedded with the Linear Quadratic Regulator (LQR) control algorithm. The LQR control method enables the UAV to maintain precise longitudinal stability by adjusting the flight control surfaces, such as the elevons, to counteract disturbances and ensure smooth, controlled flight. The microcontroller processes the sensor data in real-time, ensuring that the control inputs are applied dynamically to maintain the desired attitude and trajectory of the UAV.

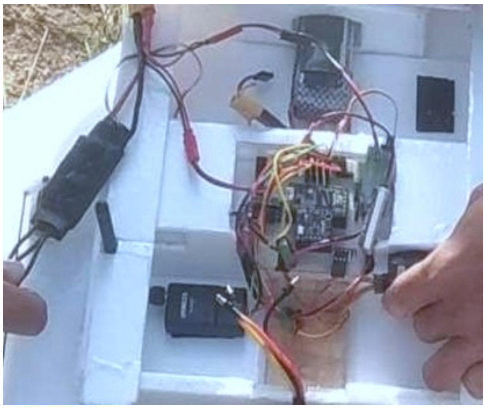

Figure 3. Electronic System of the UAV

This setup highlights the integration of multiple subsystems to achieve effective autonomous and manual flight control (Sayuti et al., 2022). The combination of the accelerometer, gyroscope, telemetry module, and LQR-based control system plays a crucial role in ensuring that the flying wing UAV performs optimally under varying flight conditions, including disturbances such as wind gusts or abrupt changes in roll and pitch (Muhammad, 2020). The system's ability to quickly stabilize and return to its desired state underscores the effectiveness of the LQR control method in enhancing the aircraft's overall performance, particularly in applications that demand high precision and reliability.

The implementation and integration of these systems are aligned with the growing demand for advanced control methodologies in the field of unmanned aerial vehicles (UAVs) (Yudha, n.d.). This research demonstrates the practical application of LQR in improving the stability and autonomy of UAVs, which is a critical factor for mission success in various sectors, including surveillance, mapping, and defense operations. The combination of theoretical research and practical implementation, as seen in this study, is valuable for advancing the field of UAV control systems and contributing to future innovations in autonomous aviation.

3. Results and discussion

3.1. Testing

The testing of the LQR control system was conducted by flying the UAV using a remote control to manage the thrust motor speed, while the attitude stability was controlled through an LQR algorithm implemented within the microcontroller. Prior to system testing, tuning of the weighting constant Q was performed to determine the optimal feedback gain value. The tuning of Q aimed to achieve the best feedback gain (K) value, which would result in stable flight with the roll and pitch angles approaching 0°. The optimal tuning results for Q were presented in Table 1, showing the corresponding feedback gain (K).

Table 1. Conversion Table of Q to Gain K

Q	***K***
$\begin{bmatrix} 0 & 0 & 0 & 0 & 1{,}01 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3{,}92 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 4{,}5 & 2{,}3 & 0 & 0 \end{bmatrix}$

The best tuning results obtained from Table 1 were a Q value of 1.01 for Qϕ and 3.92 for Qωϕ. These values led to a feedback gain (K) of 4.5, enabling the aircraft to maintain stable flight. The increase in Q value is directly related to changes in the angle values and has a significant impact on the aircraft's response in maintaining its attitude near the setpoint. Larger Q values result in a larger feedback gain (K), which causes more significant changes in the angle, leading to faster correction responses by the aircraft. However, this can also result in larger overshoots. Conversely, smaller Q values produce lower feedback gains, resulting in slower response times when the aircraft adjusts its attitude towards the setpoint.

The longitudinal motion testing of the aircraft was carried out by introducing a disturbance of 20° in the roll angle. Upon applying the disturbance, the aircraft deviated from the setpoint and experienced rolling motion in both left and right directions. This rolling motion exhibited multiple overshoots, which were recorded during the testing of the longitudinal movement of the aircraft, as shown in Table 2.

Table 2. Testing Results

Respon System	**Result**			
	Tes 1	Tes 2	Tes 3	**Specification Minimum**
Rise Time (tr)	0.8	0.9	0,7	**< 1 s**
Settling Time (ts)	1.7	1.5	1.3	**< 3 s**
Overshoot	4.46	4.33	4.28	**< 4.5^0**
Undershoot	2.27	-3.38	-3.17	**> -4.5^0**
Steady	**2.88**	**2.78**	**1.37**	**± 4.5^0**

After conducting three trials, the overall response of the aircraft met the minimum specification requirements. Based on the experimental results, the best response was obtained in the third trial. Immediately after the disturbance was introduced, the aircraft deviated from the setpoint and reached an overshoot peak of 4.28° with a rise time of 0.7 seconds. The system also exhibited an undershoot of -3.17°. The aircraft required 1.3 seconds to return to the setpoint. The control method implemented on the aircraft effectively minimized the disturbance, enabling the aircraft to maintain attitude stability. The steady-state error in the aircraft's attitude was approximately 1.37°. The analysis of the best system response is illustrated in Figure 4.

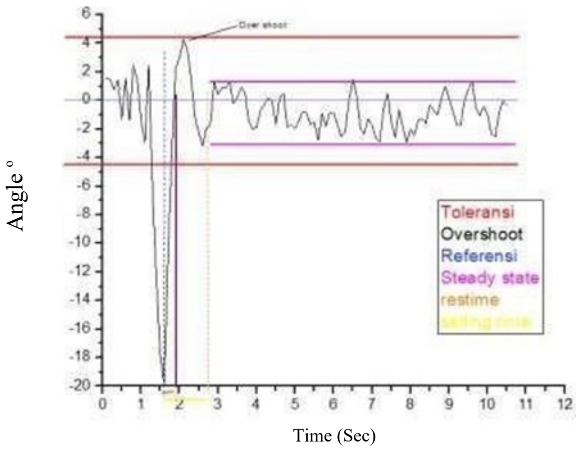

Figure 4. Longitudinal Motion Characteristics

From Figure 4, it is evident that the system experienced overshoot following the disturbance. Once the system stabilized, oscillations were observed, which indicates that the system was in a critically stable state. A critically stable state suggests that the system will continuously experience oscillations, with errors tending to approach the upper or lower limits, yet still within the acceptable tolerance of ±4.5°. The average error represents the steady-state error in the system's behavior.

Based on the conducted tests, the implementation of the LQR control method on the flying wing aircraft effectively minimized disturbances in the roll angle, allowing the aircraft to return to a stable state. This demonstrates that the roll angle control has a significant impact on the aircraft's ability to maintain longitudinal attitude stability. The aircraft's capability to return to the setpoint confirms that the implemented control system is effective in stabilizing the UAV under varying conditions.

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4. Conclusion

In conclusion, there should be no references. The conclusion contains the facts obtained, sufficiently answers the problem or research objectives (do not constitute further discussion); State possible applications, implications and appropriate speculation. If necessary, provide suggestions for further research.

Credit authorship contribution statement

Author Name: Conceptualization, Writing – review & editing. **Author Name**: Supervision, Writing – review & editing. **Author Name**: Conceptualization, Supervision, Writing – review & editing.

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