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STALL-HANDLING STABILITY CONTROL FOR CLIMBING AND DIVING MANEUVERING UAVS

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Abstract. *Fixed-wing Unmanned Aerial Vehicle (UAV) is expected to recover after experiencing a stall or losing its lifting power. Stalls happen when the Angle of Attack (AoA) increases beyond its maximum value resulting in its lifting force being smaller than the weight of the UAV. This paper uses Linear Quadratic Regulator (LQR) and Fuzzy Logic in the full-state feedback gain control. Stall control can be done by regulating the gain value so that the angle of attack returns to its normal value resulting in the UAV flying in a straight and horizontal trajectory, with the absence of rotational roll, pitch and yaw movements on its axis. Stall recovery control is executed when nose up and nose down stalls happen. This study's results show that the system's responses match that of the intended specification. The UAV has also been able to return to the angle of attack of 31°. The value of 31° is the critical limit for the angle of attack for stalls not to happen. This shows that the UAV can put the angle of attack back to its normal value.*
Keywords: LQR, Angle of attack, Full-state feedback, Fuzzy Logic

1. **Introduction.** An Unmanned Aerial Vehicle (UAV) is an aircraft without a human being that flies using aerodynamical forces. It can maneuver by itself using autopilot systems or remotely controlled by an operator from the ground [1]. UAVs can be categorized into rotary-wing, fixed-wing, flapping-wing, and blimp UAVs [2]. Each of these four categories of UAVs exhibits six Degrees of Freedom (DoF) of three translational motions (longitudinal, lateral, and vertical), and three angular motions (pitch, roll, and yaw). In a fixed-wing UAV the three angular motions can be achieved by moving the actuators of aileron for roll, elevator for pitch, and rudder for yaw [3].

In accordance with the UAV basic principles, a fixed-wing UAV also experiences 4 types of forces: thrust, drag, lift, and gravitational force (weight). Trust and lift enable the UAV to fly (leave the ground), and lift and weight prevent the UAV from flying (stay at the ground) [4].

A fixed-wing UAV may experience a stall or lose its lifting power. Stalls happen when the Angle of Attacks (AoAs) increase beyond their maximum values such that the lift is less than the weight. The AoA is the angle formed from the direction of the air towards the reference line on the UAV wing. The reference line is the line connecting the front end and the rear end at the mean point of the UAV wing. A stall is initiated by the presence of the turning thrust known as the staged stall, or the presence of an abrupt change in the deflection known as an abrupt stall.

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Stall recovery in a UAV has been done by a method utilizing a Fuzzy Logic technique [5]. However, this approach faces a multi-overshoot situation after the stall recovery reaches 6% and requires 10 seconds to put the AoA back to its normal value, resulting in the instability of the attitude. This situation can be dangerous since it may result in the crashing of the UAV to the ground. This paper proposes a method based on the Linear Quadratic Regulator (LQR) control.

An LQR control is an optimal modern control to recover a UAV from a stall condition. LQR is also a Multiple Input Multiple Output (MIMO) modern control system based on state-space analyses [6,7]. LQR is more complex than any of classical control such as a Proportional Integral Derivative (PID) control which can only handle Single Input Single Output (SISO) [8-10].

An LQR control method uses the notion of state to control the attitude and velocity of the UAV [11]. A state in a UAV consists of angular rotational motion and flying velocity of the UAV together with their values as time progresses. The state is measured using the Inertial Measurement Unit (IMU) sensors, and the airspeed sensor [12]. The outputs of those sensors are then processed using the LQR control algorithm and the outputs are used to control the attitude and flying velocity of the UAV to their optimal values to prevent a stall from happening.

The rest of the paper is structured as follows: Section 2 addresses the problem statement and preliminaries, Section 3 describes the control design, Section 4 discusses the experimental results and performance analysis, and finally, Section 5 concludes the paper.

2. **Problem Statement and Preliminaries.**

The stall recovery phases require a control system that can regulate the rotational motions of the UAV [13]. These motions are the motions that happen when stall recovery has found the setpoint detected from the altitude sensor. A scenario of the UAV movement is required to execute the recovery phases, and the control systems need to read the pitch angle and the changes in the altitude.

The stall recovery is made by flying the UAV past its AoA maximum. During stall recovery, the pitch angle deflection is obtained from the equation connecting the lift force and the UAV's AoA.

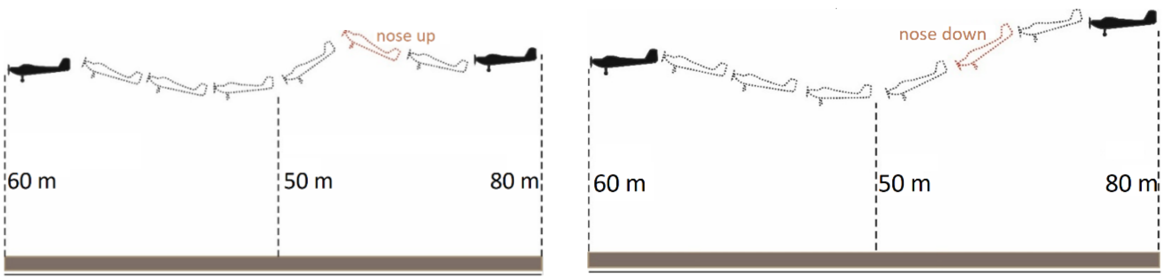
$$Fl = \frac{1}{2} C_l \cdot V^2 \cdot \rho \cdot A \tag{1}$$

$$Fl \geq W \cdot \cos\theta \tag{2}$$

$$\theta \leq \cos^{-1}\left(\frac{Fl}{W}\right) \tag{3}$$

Equation (1) is the formula used to get the lift from the UAV [14]. When climbing and swooping, the UAV will produce a different lift coefficient (C_l) when cruising. The lift coefficient was determined using software simulation and obtained a value of 0.670 when the AoA of the UAV was 31°. This value is a threshold value so that the UAV does not stall. Equations (2) and (3) are used to find the pitch angle deflection reference when performing stall recovery. The equation compares the lift's value with the UAV's weight and produces a reference pitch angle of 30° up and down.

The stall recovery stage is divided into two, namely, the stall recovery stage during climbing and diving [15]. Stall recovery is started by flying the UAV up to ±60 meters above the Earth surface. A climbing stall happens when the UAV is tilted upward such that its nose is higher than its tail. This is shown in Figure 1(a). During a climbing stall recovery stage, the UAV faces upward with an angle of attack above its maximum value, and its velocity below its stall speed. Then, the UAV will decrease its pitch angle deflection to achieve its minimum angle of attack by forcing the UAV to face downward. When it finds the intended angle, the UAV will fly in equilibrium.



(a) (b)

Figure 1. Recovery stages from (a) stall climbing and (b) stall diving

The diving stall is a condition in which the UAV nose is lower than its tail. The diving stall recovery is carried out by putting the angle of attack back to its minimum value to allow the UAV to fly in equilibrium. The diving stall recovery phases can be seen in Figure 1(b).

The electronic systems design is illustrated in Figure 2. A 10-DoF IMU [16] sensor has been used. The IMU sensor consists of an accelerometer and a gyroscope to measure angle and angular velocity of roll, pitch, and yaw with respect to the Earth axis using a technique called Digital Monitoring Processing (DMP) sensor fusion [17]. A barometric sensor has been used to measure the latitude of the UAV based on the air pressure which can be converted to latitude. An airspeed sensor is used to measure the velocity of the airflow. The IMU sensor, the airspeed sensor, and the microcontroller are connected using the Serial Peripheral Interface (SPI) communication channels.

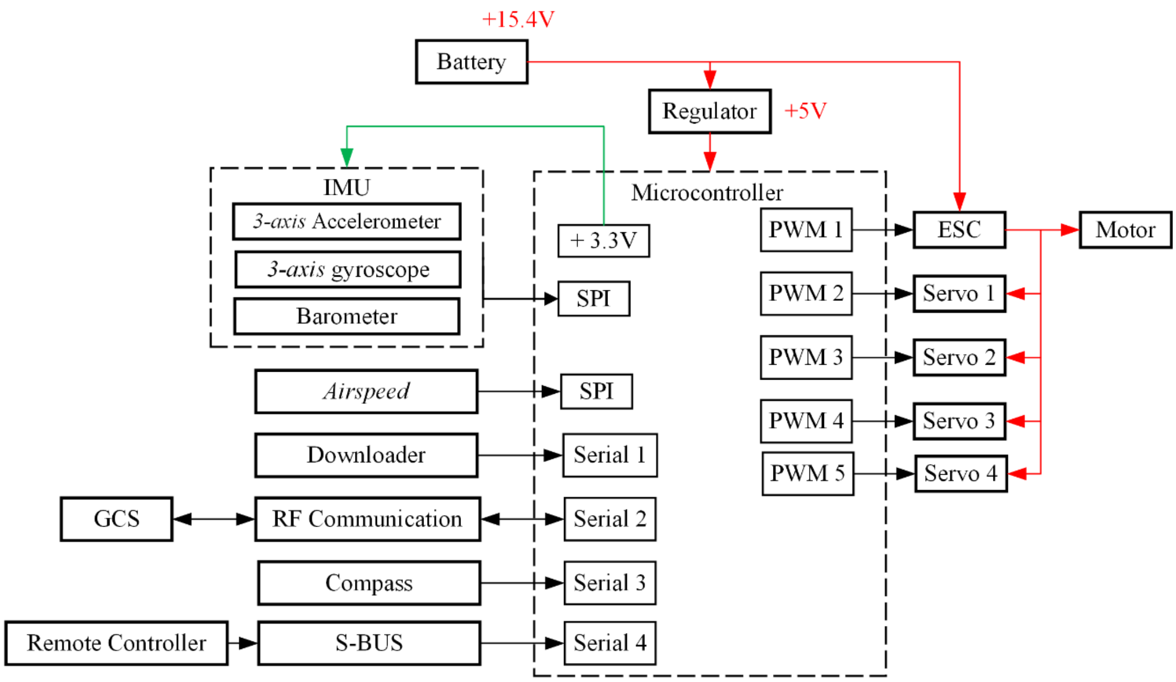


Figure 2. Electronic systems design

The microcontroller will instruct the servos to cause motions on the aileron, rudder, and elevator. The STM32F407 microcontroller has been used. The microcontroller oversees data processing and execution of the algorithm of the UAV system. The outputs of the systems will control brushless motors to thrust the UAV and servos to move the aileron, elevator, and rudder of the UAV. Servo 1 and servo 2 are used to cause a motion on the left and right ailerons. Servo 3 is used to move the elevator, and servo 4 to move the rudder.

The angular velocities of the brushless motors are regulated using the Electronic Speed Controller (ESC) and the Pulse Width Modulation (PWM) outputs of the microcontroller.

3. **Control Design.** The equations of rotational motion of an airplane are generally shown in (4), (5), and (6) [18].

$$I_{xx}\dot{p} + (I_{zz} - I_{yy})qr = \tau_1, \quad \dot{p} = \frac{(I_{yy} - I_{zz})qr}{I_{xx}} + \frac{1}{I_{xx}}\tau_1 \tag{4}$$

$$I_{yy}\dot{q} + (I_{xx} - I_{zz})pr = \tau_2, \quad \dot{q} = \frac{(I_{zz} - I_{xx})pr}{I_{yy}} + \frac{1}{I_{yy}}\tau_2 \tag{5}$$

$$I_{zz}\dot{r} + (I_{yy} - I_{xx})pq = \tau_3, \quad \dot{r} = \frac{(I_{xx} - I_{yy})pq}{I_{zz}} + \frac{1}{I_{zz}}\tau_3 \tag{6}$$

where τ_1, τ_2, and τ_3 are roll, pitch, and yaw torques, respectively, and p, q, r are roll, pitch, and yaw angular velocities.

The flight stabilizer equation is obtained from the torque equation for the UAV. Based on Equations (4), (5), and (6), it takes the value of the moment of inertia and mass of the UAV. The UAV has a basic shape, namely a beam. So, we assume calculating the inertia of the UAV's body, wing, and tail will be like calculating the inertia of the beam.

The control systems to be designed employ the LQR method together with Fuzzy Logic. LQR aims at reaching a state having constants references represented by reference states. The block diagram of the control systems is shown in Figure 3. The control systems in this paper use six states as basic references of the control parameters. These states are

1) the roll angle (ϕ)
2) the pitch angle (θ)
3) the yaw angle (ψ)
4) angular velocity of roll (p)
5) angular velocity of pitch (q)
6) angular velocity of yaw (r)

In Figure 3 the control systems design for the stall recovery is shown. The reference values consist of the roll, pitch, and yaw, together with their respective velocities. The value of the pitch angle is based on the critical angle of attacks.

The AoA (α) can be calculated using Equation (7). When the UAV is flying, the AoA can affect the airflow speed on the UAV wing. Changes in the value of the AoA can affect the lift from the UAV.

$$\alpha = \tan^{-2}\frac{V_z}{V_x} \tag{7}$$

The fixed-wing UAV algorithm consists of several sub-programs. The main program processes the instructions enabling the UAV to carry out a stall recovery automatically in accordance with the embedded sequences and logics. The sub-program of the software consists of setup, sensor fusion, and stall recovery control.

The first step of the algorithm is declaring the variable and calling the library. Then, the flight parameters are set. We sent these parameters to the ground station computer via telemetry. Once the parameters have been set, the PWM signal initiates the brushless motors and servos. The movement of the servos indicates this status, and the ESC beeps when the PWM signal arrives at these actuators. The IMU and airspeed sensors are then measured and sent via telemetry.

The control program, LQR with Fuzzy, works to provide a gain value to the system, whose output will be feedback to the control. LQR, as a fixed gain, serves as the primary stabilization method for the fixed-wing UAV flight. When a stall occurs, which is indicated by a change in AoA that exceeds the critical angle of the UAV, the static gain of the LQR cannot handle this condition.

For this reason, a dynamic gain compensator is generated using Fuzzy Logic. As the name implies, this gain compensator adds to the gain value of the LQR-based stabilizer. This gain uses the concept of gain scheduling, but by utilizing Fuzzy Logic, this gain will

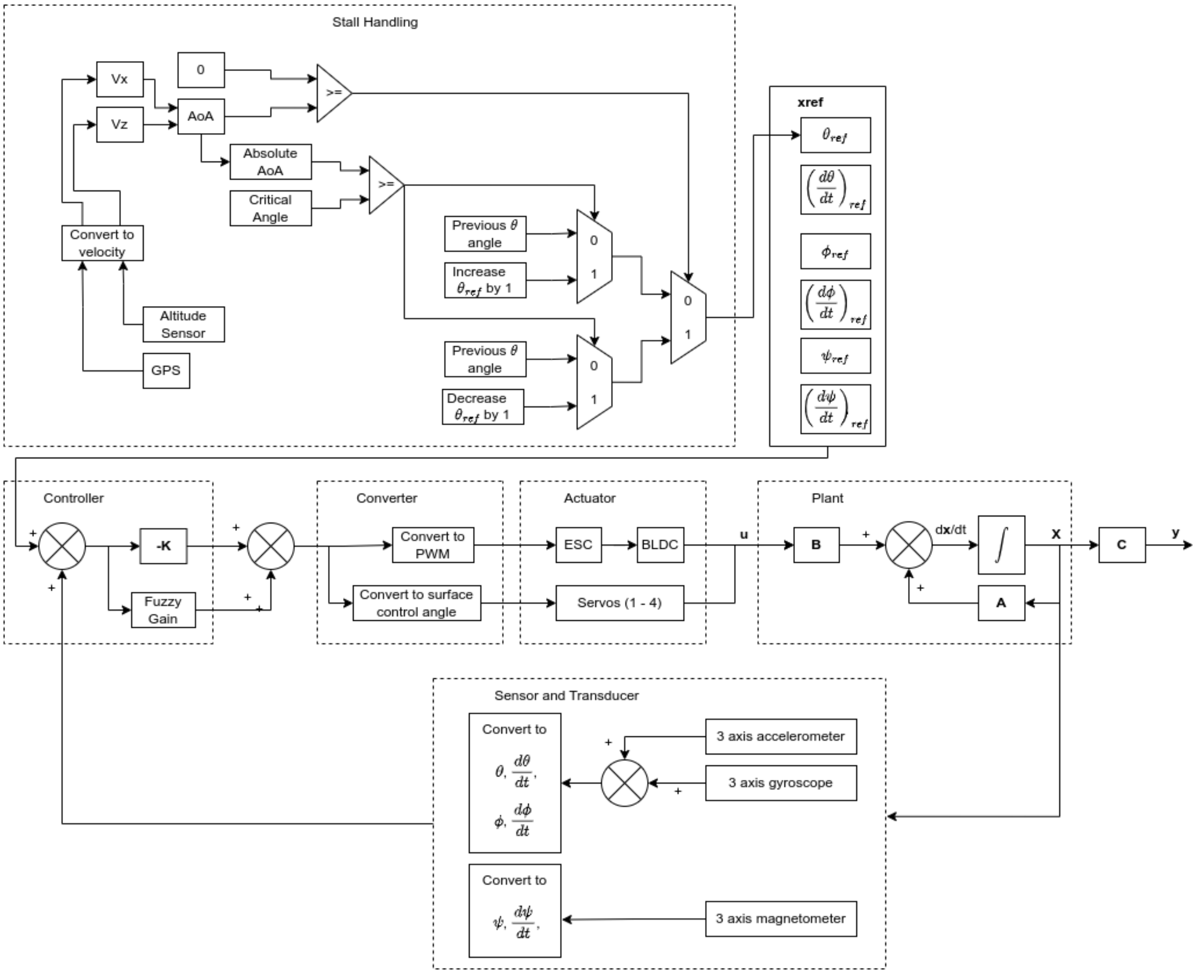


Figure 3. The control systems block diagram

change subtly compared to conventional gain scheduling. When there is no stall, then the value of this gain is 0.

This compensator gain is formed using a fuzzy set where the fuzzy set's boundary values are obtained through semi-manual stall recovery experiments by sending a fixed compensation gain value from the ground to the UAV via a telemetry module. The results of this experiment then form a fuzzy set and generate a dynamic gain based on Fuzzy Logic to compensate for the static LQR method.

The control system's output is converted to the rotation of the brushless motor and the servos. The servo and brushless motor determine the flight attitude of the UAV in such a way that the UAV will fly at the desired set point in a horizontal and straight trajectory.

The testing of the control systems, LQR and Fuzzy, for the stall recovery is carried out by first flying the UAV. The initial testing is to see the control systems capabilities in keeping the latitude and flying direction of the UAV. After that, the capabilities of the control systems to carry out the stall recovery are tested during climbing and diving stalls.

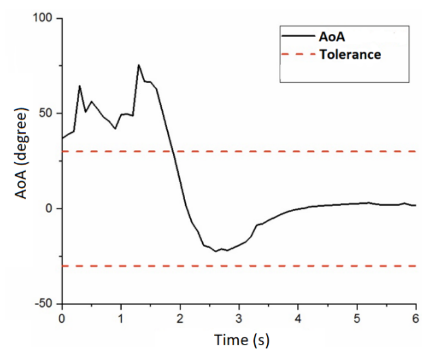
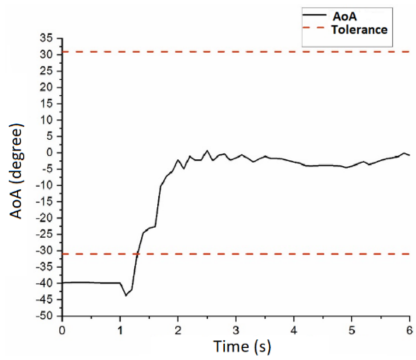
The first testing has been done by flying the UAV in the stable mode so that the UAV will fly in a stable condition with a straight flight direction. Then the UAV is set to the auto mode. In the auto mode the UAV responses will be observed in its outputs and altitude sensors.

The second testing is related to the stall recovery. The testing has been done by flying the UAV in the manual mode then setting the UAV into climbing and diving stalls with a pitch angle above the AoA of 30° upward and downward when the UAV reaches an altitude of ±80 meters above the Earth surface. Once the UAV is in a stall condition the mode is changed to the stable mode to recover from the stalls. The climbing and diving stall testing aims at observing the control system responses in attempting to recover from the stalls quickly and precisely.

In all the testing, the UAV capabilities in responding to altitude changes will be observed via measuring the outputs and the altitude sensors. The systems response is in the form of how stable the UAV is when performing stall recovery stages based on the computed coefficients. The results will be measured, stored, and validated. The results are implemented in the flying testing to observe the UAV responses when facing a real stall condition.

4. **Results and Discussions.** In this section, stall recovery testing for a fixed-wing UAV using LQR and Fuzzy methods in a full-state feedback control setting is described and explained. The stall recovery testing is categorized into climbing stall and diving stall testing. The result of the testing is illustrated in Table 1.

Table 1. Results of testing

<table>
<tr><th>Legend</th><th>Stall climbing</th><th>Stall diving</th></tr>
<tr><td>Angle of Attack</td><td>
</td><td>
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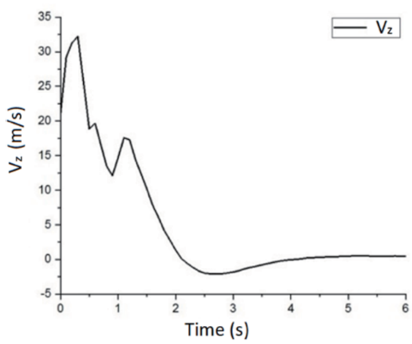
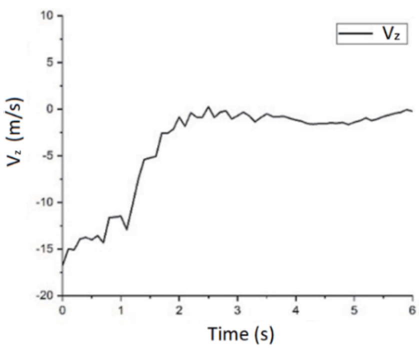
<tr><td>z axis speed V_z</td><td>
</td><td>
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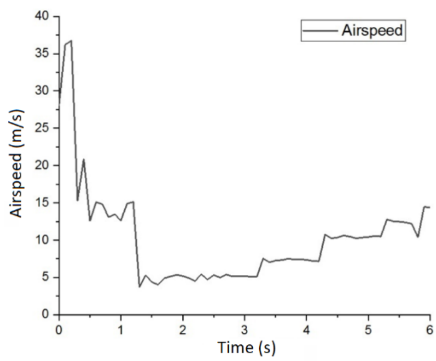
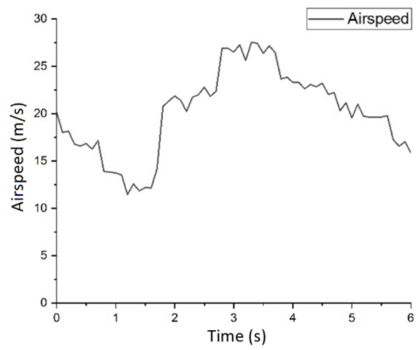
<tr><td>x axis speed V_x (based on airspeed)</td><td>
</td><td>
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</table>

In this study, the AoA reference of 31° upward and downward has been calculated by a simulation on a JavaFoil program when the lifting force of the UAV is bigger than the weight of the UAV. From the graph, angle of attack in the case of stall climbing, the angle of attack after 1 second has increased up to 1.3 having a maximum of angle of attack of 75.64°.

The value of angle of attack is related to the velocity of the UAV shown in the axes of x (V_x) and z (V_z). The UAV velocity in the z axis (V_z) can be computed by taking the derivative of the altitude measured by the barometer multiplied by the cosine of the pitch angle. The UAV velocity in the x axis (V_x) is the reading of the airspeed sensor. The angle of attack will return to the critical angle of attack when the value of the velocity in the x axis (V_x) is less than that of the z axis (V_z) of the UAV. This is proven by comparing the values of V_z with that of V_x of the airspeed.

It is shown in the graph that the angle of attack during stall climbing at 1.9 seconds the angle of attack has returned to the value of the critical angle of attack of 27.54° because the value of the airspeed has started to increase to ±5.35 m/s accompanied by the decrease in the axis velocity V_z of the UAV to ±2.79 m/s. Based on this, it can be said that the UAV has been able to carry out stall recovery optimally without experiencing a multi-overshoot condition.

From the graph of stall diving AoA, the UAV can return the critical angle of attack within 1.4 seconds with a value of 24.9° after experiencing an increase in the airspeed of ±11.85 m/s while at the same time the velocity V_z is ±5.40 m/s less than the airspeed of the UAV.

During the stall recovery stages, the LQR control systems will regulate the stabilizing attitude for the motions of roll and yaw of the UAV with respect to the disturbances. The time needed to recover from climbing or diving stalls is no more than 2.5 seconds. This is already faster than previous research which needed 10 seconds. In a stall recovery a gain value of K_p is given to control the pitch attitude responses of the UAV to reach its reference value. Gain K_p for the stall recovery stages is given a value of 5.02. This value is based on the tuning in the field by observing the pitch response during a stall recovery. The same as that of the pitch stabilization, during a climbing or diving stall recovery, the Fuzzy method is used as a compensator.

The Fuzzy control process receives an input in the form of errors and delta errors based on LQR control. In turn, the output will be controlled by LQR control in the form of a constant value. The Fuzzy system functions as the gain tuner, scheduled when a disturbance happens.

It can be said that the UAV has shown to be able to stabilize the UAV attitude in performing the stall recovery stages using the methods of LQR and Fuzzy in a full-state feedback control setting.

5. **Conclusions.** Based on testing, observation, and analysis of the results, it is concluded that the fixed-wing UAV has been proven to recover from stall climbing and diving using LQR and Fuzzy Logic in this paper. The Fuzzy method successfully compensates the static LQR method so that a compensated gain based on Fuzzy Logic can handle stability only when a stall occurs. The fixed-wing UAV can restore the stall state within 2.5 seconds, indicated by the AoA value being lower than the critical angle. It is concluded that the LQR and Fuzzy methods have stabilized the UAV's attitude to recover from stall conditions in full-state feedback control. For further research, stabilization methods can be developed to handle more extreme flying.

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