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WAYPOINT TRACKING OF A FIXED-WING UAV USING THE L1 CROSS TRACK ERROR CONTROL

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Abstract. *The utilization of fixed-wing Unmanned Aerial Vehicle (UAV) technology has grown not limited to the military field but also in monitoring, mapping and aerial photography. One of the activities that are often carried out is monitoring the area and aerial photography. To carry out this mission, the UAV must be able to trace the waypoint lines. The waypoint control system made in this study uses the Linear Quadratic Regulator (LQR) method to maintain the stability of the lateral and longitudinal attitudes of the vehicle during the waypoint tracking mission. In navigation control, the L1 controller method generates the value of lateral acceleration and is converted into an angle value to navigate the UAV to the waypoint line. The results of this study are the UAV can maintain the trajectory while simultaneously tracking the six waypoint coordinates autonomously using the Linear Quadratic Regulator (LQR) and the L1 controller navigation method.*

Keywords: LQR, UAV, Bearing angle, L1 controller, Control

1. **Introduction.** Unmanned Aerial Vehicle (UAV) can be used for the civilian and military fields. UAVs are no longer limited to the military area but can also be used by civilians [1,2]. A fixed-wing UAV on a surveillance mission somewhere must have the ability to maintain its position while travelling to the destination's coordinates. UAV requires a Global Positioning System (GPS) to obtain accurate latitude and longitude information to complete its mission [3]. When flying to a point, the UAV requires initial coordinates and destination coordinates using data from a GPS receiver [4]. If a line is drawn between the two points, it will form a waypoint that the UAV should have passed [5]. Waypoint itself is a UAV flight path in the form of an imaginary straight line taken from the coordinates of the flight destination [6]. A fixed-wing UAV goes through several waypoints in carrying out a surveillance mission, so a control system is needed on the UAV to maintain stability and keep it on the waypoint line [7].

Based on the description above, other control methods are needed to maintain longitudinal and lateral moves that are reliable and adjust the UAV's attitude not to experience steady-state errors. One of the control methods used is the Linear Quadratic Regulator (LQR) [8].

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A study showed that the waypoint line tracing by a fixed-wing UAV was carried out using only the LQR or SMC control method [9-11]. The UAV was still unable to maintain it on the waypoint but only support it towards a predetermined point. This may be because the LQR control system used is only used to improve the yaw response of the UAV during the waypoint tracking flight mission.

Therefore, a control method is required to maintain the UAV's attitude and stay on the waypoint line. Several control methods can be used to solve these problems. One combines two techniques: LQR as an attitude controller and L1 controller as a waypoint tracking controller. The L1 controller is a method that has been widely used in many UAVs for tracking waypoints [12]. This method helps set up controllers on the UAV when travelling in a straight line. This method also contains an element of anticipatory control which is useful when tracing lines. The results of this study aim that the UAV can maintain the trajectory while simultaneously tracking the six waypoint coordinates autonomously using the Linear Quadratic Regulator (LQR) and the L1 controller navigation method.

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.** In this study, the UAV control system uses the LQR method and the L1 controller navigation. The LQR method is a regulator control that aims to bring the system to a predetermined state by setting the error to zero with minimum cost. LQR can be used to optimize full-state feedback control. Further, the L1 controller's navigation method is the cross-path error control of the UAV's flight, whose purpose is to enable it to track waypoints.

The navigation method of the L1 controller is a cross path error control that aims to allow the UAV to track waypoints [6]. This method uses inertia velocity in the calculation of lateral acceleration (lateral acceleration command), which increases the ability to cope with changes in UAV speed due to external disturbances, such as gusts of wind. The logic in the method used is to adjust the L1 distance to the desired path and generate the lateral acceleration command using that reference [12].

The scheme of the waypoint search mission carried out using the L1 controller method can be seen in Figure 1. The technique used is a straight-line tracking type [13].

$$\eta = \beta_L - \beta_h \tag{1}$$

$$a_{S_{cmd}} = 2\frac{V^2}{L_1}\sin\eta \approx 2\frac{V}{L_1}\left(\dot{d} + \frac{V}{L_1}d\right) \tag{2}$$

where

η = error angle between the UAV course and L_1 bearing

$\beta_L = L_1$ bearing

β_h = the UAV course

$a_{S_{cmd}}$ = acceleration command sideways

V = ground speed

L_1 = length of the flight distance to the desired flight path

d = the shortest distance between the UAV positions and the desired flight path.

The non-linear guide logic provides a control element for crossover errors. The ratio of the flight speed V and the length of the distance L1 is an essential factor in determining the controller. For example, a small value for L_1 will result in a high control gain and the ratio L_1 or V determines the controller time constant.

Determination of one of the components of the L1 distance can be determined by performing a stability analysis by entering the linear model and the derivative linear controller. The model should include UAV dynamics.

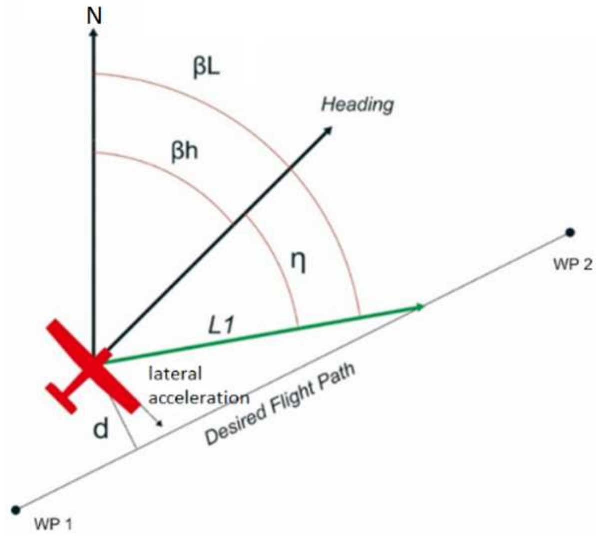


Figure 1. Linear model for straight-line following case

Furthermore, assuming there is no inner-loop dynamics, then $a_{S_{cmd}} = -\ddot{d}$. So Equation (2) is equivalent to Equation (3).

$$\ddot{d} + 2\zeta\omega_n\dot{d} + \omega_n^2 d = 0, \quad \zeta = \frac{1}{\sqrt{2}}, \quad \omega_n = \frac{\sqrt{2}V}{L_1} \tag{3}$$

where
$\ddot{d}$ = second order of d
ζ = damping ratio
ω_n = natural frequency.

Equation (4) shows a linear model from the initial Equation (3). From this model, it can be seen that the system is a second-order system that always has a damping ratio of 0.707, and the natural frequency is determined by the UAV speed ratio and the distance between it and the desired path (L1).

$$a_{S_{cmd}} = K_L \frac{V^2}{L_1} \sin\eta \tag{4}$$

$$L_1 = q_L V \tag{5}$$

$$q_L = P_L \times \frac{\zeta_L}{\pi} \tag{6}$$

$$K_L = 4\zeta_L^2 \tag{7}$$

where
$K_L = L_1$ gain
ζ_L = controller parameters, the damping at L_1
P_L = controller parameters, the period at L_1 which is the inverse of proportional
$q_L = L_1$ ratio.

In Equations (5) and (6), it can be seen that the navigation control on controller L1 has controller parameters P_L and ζ_L. The P_L parameter is the period at L1, which is the inverse of proportional and ζ_L is the damping at L1. In this study, the existing natural attenuation model was used with a value of 0.707. The damping value of 0.707 is used to obtain the calculation of the L_1 gain K_L as in Equation (7), and the result is 2. This K_L value can then be applied to the basic Equation (4) to control L1 to become Equation (8).

$$a_{S_{cmd}} = 2\frac{V^2}{L_1} \sin\eta \tag{8}$$

3. **Control Design.** The stabilizer control system uses the LQR method as a regulator control to bring the system to a state with zero error [14]. Figure 2 shows the block diagram of the UAV control system used in this study.

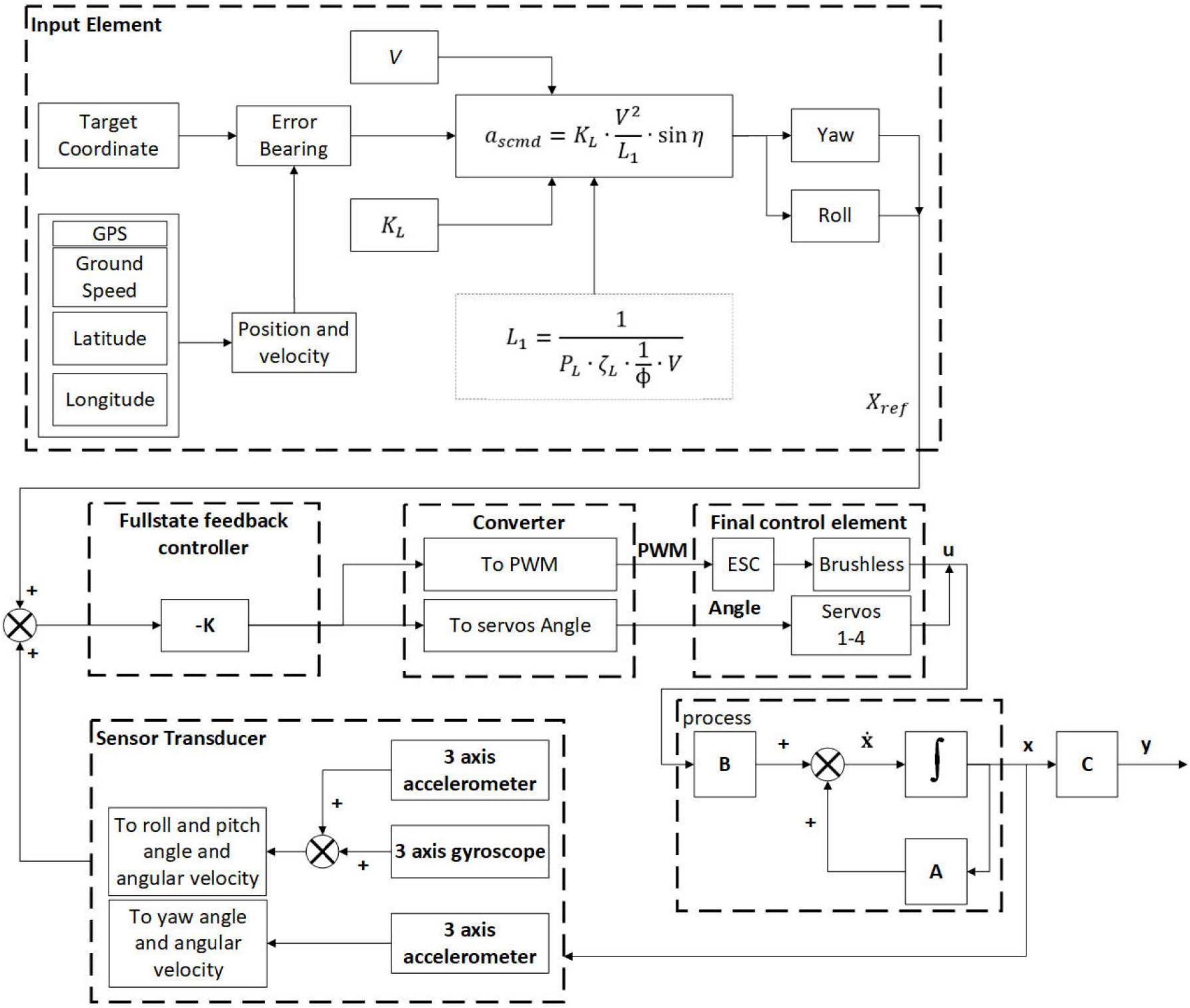


FIGURE 2. Control system block diagram

The control system in this study uses six conditions as an essential reference for control parameters [14]. They are

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

The fixed-wing UAV model for rotational motion can be derived from Equations (9), (10), and (11) which are the equations for torque in the fixed-wing aeroplane model.

$$\dot{p} = \frac{(I_{yy} - I_{zz})qr}{I_{xx}} + \frac{1}{I_{xx}}\tau_1 \tag{9}$$

$$\dot{q} = \frac{(I_{zz} - I_{xx})pr}{I_{yy}} + \frac{1}{I_{yy}}\tau_2 \tag{10}$$

$$\dot{r} = \frac{(I_{xx} - I_{yy})pq}{I_{zz}} + \frac{1}{I_{zz}}\tau_3 \tag{11}$$

where

τ_1 = roll torque
τ_2 = pitch torque
τ_3 = yaw torque

Based on Equations (9), (10), and (11), an aeroplane model for anti-rotation motion is obtained. The three equations are then converted into state-space, as shown in Equation (12).

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{12}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{p} \\ \dot{\theta} \\ \dot{q} \\ \dot{\psi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{(I_{yy}-I_{zz})*r}{I_{xx}} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & \frac{(I_{zz}-I_{xx})*r}{I_{yy}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & \frac{(I_{xx}-I_{yy})*q}{I_{zz}} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \phi \\ p \\ \theta \\ q \\ \psi \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{I_{xx}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{I_{yy}} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{I_{zz}} \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix}$$

4. **Main Results.** This section describes the results of the waypoint tracking tests on fixed-wing UAVs using the LQR and L1 controller methods. Stabilizer control settings are conducted by tuning the component values of each rotational movement to get the most optimal system response. The parameter set is the LQR control parameter which consists of six **Q** amplifications. The LQR method will generate multiple gain values for full-state feedback. The full-state feedback advantage is then tested on the UAV during flight to determine the steady-state error response when the UAV is assigned a specific noise value.

There are several steps to carry out this tuning. Tuning starts automatically through the LQR control simulation process using simulator software. The full-state feedback return value helps obtain an initial reference value that will apply throughout the system. The control simulation uses a mathematical model of the UAV dynamic system, which will be controlled and represented in state space. Then the stabilizer control of each rotational motion is simulated to optimize it to be tested automatically.

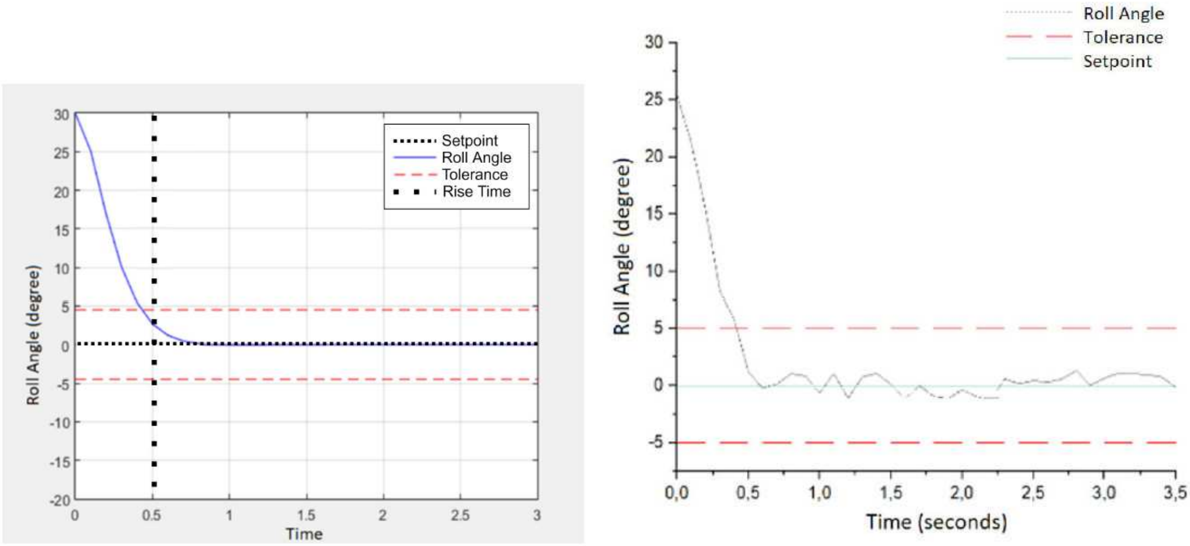
The components of the **Q** value that are auto-tuned in this system are

- Q_ϕ (for roll angle)
- Q_p (for roll angular velocity)
- Q_θ (for pitch angle)
- Q_q (for pitch angular velocity)
- Q_ψ (for yaw angle), and
- Q_r (for yaw angular velocity)

Stabilizer simulation is carried out by automatically tuning the **Q** values. The LQR method by using these **Q** values will produce a full-state feedback gain value **K** [15].

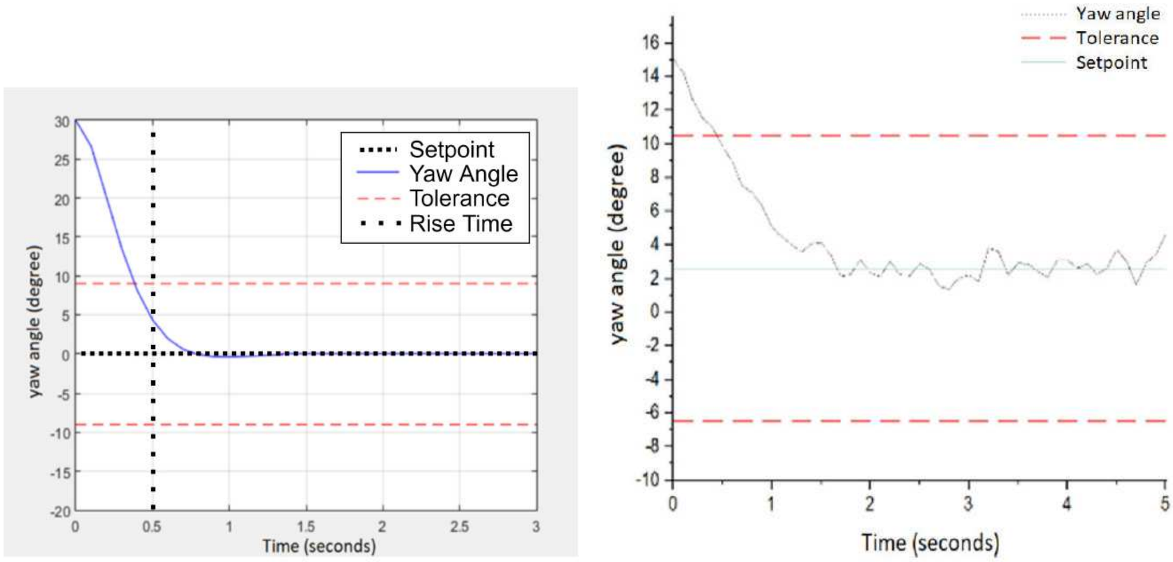
Based on Figure 3(a), the response time of the anti-roll simulation can be up to 0.5 seconds without overshoot. This result is achieved through the roles of Q_ϕ and Q_p, which give the gain values $K_{\phi.\tau_\phi}$ and $K_{p.\tau_\phi}$. The greater the **Q** values are given, the faster the system response will be because the torque τ_ϕ value is also more significant. However, if the value given of Q_ϕ is too large, it will be causing some overshoots. This condition is caused when the torque τ_ϕ increases and the system becomes very sensitive to disturbances, so it is necessary to use damping gain Q_p.

During validation, the **Q** tuning results from the simulation are entered into the UAV system through the Ground Control Station (GCS). Then the UAV will be flown in stabilization mode. The UAV will be given interference in the form of a forced roll motion with a specific angle value suddenly from the GCS to test its anti-unwanted roll response. Figure 3(b) shows that at 0 to 0.5 seconds, the UAV is given a roll fault with a peak value of 25.4°. The disturbance given causes instability in the attitude of the UAV so that full-state feedback control is used to overcome the disruption. The gain system can adjust the aileron motion, resulting in the LQR control output in a rotating torque opposite a given fault direction. The ailerons swings aim to return the UAV to its reference roll position, which is 0°. Furthermore, the data from the system validation



(a) (b)

FIGURE 3. Roll stabilizer: (a) Simulation (b) validation



(a) (b)

FIGURE 4. Yaw stabilizer: (a) Simulation (b) testing

shows that the control system has been able to stabilize the roll motion according to its reference value with a rise time of 0.5 seconds and a settling time of 1 second. The system is still experiencing a 0.11° steady-state error, which is still within tolerance.

Figure 4 shows the simulation and validation result of the yaw stabilizer. Figure 4(a) shows the anti-yaw simulation, which resulted in a rise time of 0.5 seconds and no overshoot was found. These results can be achieved with the results of automatic tuning of the best **Q** values, namely Q_ψ and Q_r, to produce gain values $K_{\psi.\tau_\psi}$ and $K_{r.\tau_\psi}$. The higher the Q_ψ value, the greater the $K_{\psi.\tau_\psi}$. This condition can cause overshoot in the system, so that damping is needed using Q_r to avoid overshoot.

The navigation control on this UAV's landing system uses the L1 controller method, which produces lateral acceleration for the UAV as a waypoint line tracking parameter. In calculating the lateral acceleration, there is a component of the UAV speed and the length of the L1 line. The L1 line is the line between the UAV and the desired flight path. In this study, the component that can be adjusted to get maximum results is the L1 line. There are two essential components in the L1 line length adjustment, namely the L1 period and L1 attenuation.

The L1 period affects the time constant ratio of the L1 controller, while the L1 attenuation affects the damping when the UAV crosses the target waypoint line while turning towards the next direction. At L1 attenuation, the value is determined by the system as in Equation (7). So, the component value in this system that can be tuned is the L1 period. The L1 period value adjustment is based on the UAV's response when carrying out a waypoint tracking mission. The UAV will be flown along with six-coordinate points, which resemble the letter S horizontally. Then the L1 period is tuned so that the UAV can track the waypoints to match the imaginary path formed from the six predetermined coordinate points. So after the flight mission is carried out, the results will show a trajectory that resembles the letter S horizontally (as seen in Figure 5(b)).

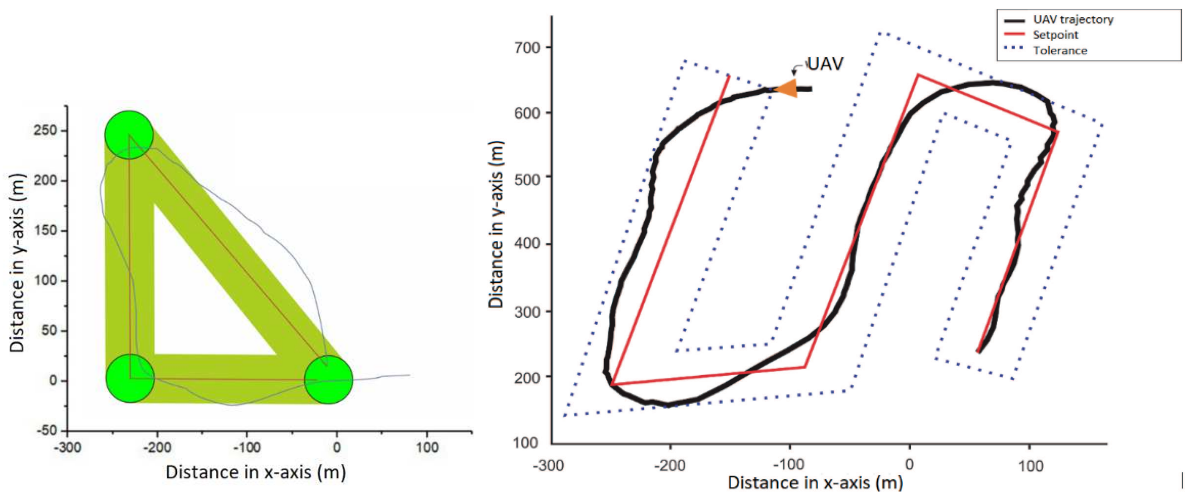


Figure 5. Results of direct testing of waypoint missions (a) without using the L1 controller, (b) using the L1 controller

If we do not use the L1 controller, then Figure 5(a) shows the UAV is not trying to return to its flight path when suddenly exiting the flight path, but only tends to the waypoint. This causes the UAV to fly outside its proper flight path even though it will still go to the way point. If using the L1 controller, the UAV will keep trying to return to the desired flight path, not just going to the waypoint. Following Figure 5(b), the UAV can fly without tracing an imaginary line between 6 waypoints without going out of its flight tolerance limits.

5. **Conclusions.** Based on the results of the tests, observations and analyses that have been obtained, it can be concluded that the UAV has been able to maintain the trajectory while simultaneously tracing the six waypoint coordinates autonomously using the Linear Quadratic Regulator (LQR) and the L1 controller navigation method. The two approaches have been designed to collaborate and have been implemented successfully. The UAV was successful in tracking the waypoints line. The deviation that occurs in the UAV from the waypoint line is still within the tolerance limit of 45 meters following a predetermined waypoint radius. The period value in the L1 method has been tuned well to produce results that are in line with expectations.

The stabilizer control response shows that the system is still experiencing a steady-state system. This response indicates that the control is stable on the fixed-wing UAV, maintaining the UAV intolerable conditions. Furthermore, with these results during the flight test, the UAV can fly steadily.

In this research, there are still things that need to be improved. Suggestions that can be used to enhance further research are the need for a simulation process to describe the condition of fixed-wing UAVs when conducting a waypoint search mission. This process is needed to determine the effect of external factors on flight performance and the trajectory.

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