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A Study of Building Automatical Landing of Fixed-Wing UAV in Lateral Wind Conditions

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A B S T R A C T

The landing process of the Unmanned Aerial Vehicle (UAV) is greatly affected by the lateral wind parameter, which often causes the UAV to deviate from the centerline of the runway during descent. This deviation may result in unstable landing trajectories, reduced precision, and increased risk of collision or structural damage, especially in complex environments such as urban areas or limited landing zones. In severe cases, strong crosswinds can cause complete landing failure or loss of control, posing threats not only to the UAV but also to surrounding infrastructure and safety protocols. Therefore, developing an automatic landing algorithm capable of adapting to lateral windy conditions is an urgent and essential task. The objective of this study is to design and simulate an autonomous landing control system that ensures the stability and accuracy of UAV landings under varying crosswind intensities. By analyzing wind dynamics and the UAV's response characteristics, the proposed algorithm applies adaptive control techniques and compensation strategies to maintain a safe descent trajectory. The algorithm is tested in multiple simulated wind scenarios to validate its performance, robustness, and practical feasibility. The results of this research serve as a foundation for implementing technical solutions in real-world UAV systems, especially in applications requiring high levels of autonomy such as cargo delivery, reconnaissance missions, or emergency support in remote areas. Moreover, this work contributes to the broader field of autonomous aerial navigation by addressing one of the key challenges in UAV operations safe and precise landing under unpredictable environmental conditions. It also opens up new directions for future research on multi-factor environmental adaptation and intelligent flight control.

Keywords: Automatic Landing, Crosswind, Fixed-Wing UAV

1. Introduction

For the design of an automatic landing control system, conventional control laws such as PD, PI, or PID controllers can be used to reduce the altitude and speed of the UAV. PD and PID controllers are typically employed to control the pitch angle and pitch rate. Additionally, state-space-based controllers, such as inverse kinematics with command filtering and state observers [1-3], are also utilized. Furthermore, optimal controller synthesis methods like H_2, H_{inf}, and H_2/H_{inf} [4], adaptive controller synthesis based on inverse kinematics theory and neural network theory [5], or fuzzy control techniques [6] are applied by researchers. Authors Shue and Agarwal [7] developed a combined H_2/H_{inf} controller for the landing process, while Ochi and Kanai [8] employed H_{inf} control techniques in the design of an automatic landing controller. In Vietnam, research on UAV automatic landing processes is still limited, with studies [13] [14] [15] focusing only on the longitudinal channel and constant wind, without considering the crosswind channel problem. On the other hand, in their research, the author has developed an automatic landing algorithm for fixed-wing UAVs in the vertical plane under wind disturbances [11]. However, to complete the research on fixed-wing UAV landing under changing wind disturbances, further foundational studies in the crosswind plane are required to apply modern control laws effectively. This is a crucial aspect in improving the automatic landing control method for UAVs, as crosswind significantly impacts the landing process. In this paper, the author focuses on clarifying and analyzing the effects of crosswind on the UAV landing process. Based on the obtained results, the author proposes a control approach using roll angle signals to control the UAV's automatic landing process in the crosswind plane under the influence of crosswind. Simulation results in Matlab Simulink demonstrate the effectiveness of the proposed approach.

2. Material and methods

To analyze the qualitative crosswind motion of the UAV, the following assumption must be made: small angles $\alpha, \vartheta, \beta, \gamma$. Under this assumption, in the absence of wind disturbances, the velocity vector $\overrightarrow{V_a}$ aligns with the ground speed vector $\overrightarrow{V_g}$. The system of differential equations describing the crosswind motion of the UAV [9] is presented in equation (1).

$$\begin{cases} -mV_g\dfrac{d\Psi}{dt} = Y_a.\sin\gamma + \left(C_y^{\delta_r}.\delta_r + C_{z\beta}\right).\dfrac{\rho.V_a^2}{2}.S - T.\sin\beta \\ J_x\dfrac{d\omega_x}{dt} = (m_x^{\varpi_x}.\dfrac{\omega_x.b_a}{V_g} + m_x^{\delta_a}.\delta_a + m_x^{\delta_r}.\delta_r + m_x^{\beta}.\beta_a + m_x^{\varpi_y}.\dfrac{\omega_y b_a}{V_a}).\dfrac{\rho.V_a^2}{2}.S.b_a \\ J_y\dfrac{d\omega_y}{dt} = (m_y^{\varpi_y}.\dfrac{\omega_y.b_a}{V_g} + m_y^{\beta}.\beta_a + m_y^{\delta_r}.\delta_r + m_y^{\varpi_x}.\dfrac{\omega_x.b_a}{V_a}).\dfrac{\rho.V_a^2}{2}.S.b_a \\ \dfrac{dx_o}{dt} = V_g\cos\Psi \\ \dfrac{dz_o}{dt} = -V_g\sin\Psi \\ \dfrac{d\gamma}{dt} = \omega_x; \dfrac{d\psi}{dt} = \omega_y \end{cases} \tag{1}$$

Where: V_g-Ground speed; $\frac{\rho.V_a^2}{2}$-Dynamic pressure; δ_r-Yaw control surface deflection angle; J_y-Moment of inertia about the Oy axis of the body-fixed coordinate system; S - Aircraft wing area; b_a-Average dynamic air pressure; Ψ -Heading angle of the flight path; ψ - Heading angle; ω_x-Angular velocity about the Ox axis;

In the case of wind disturbances acting in the horizontal plane, the velocity vector $\overrightarrow{V_a}$ deviates from the ground speed vector $\overrightarrow{V_g}$, with the angular velocity vector $\Delta\beta$. The system of equations in this case is similar to system (1), with the difference being in the expressions related to drift force, drag force, and aerodynamic moments.

To fully analyze the parameters of the system of equations (1), we consider the relationship between the speed parameters and the horizontal wind components in the ground coordinate system, which is expressed by the following equation $\overrightarrow{V_a} = \overrightarrow{V_g} - \overrightarrow{W}$ and is illustrated in Figure 1.

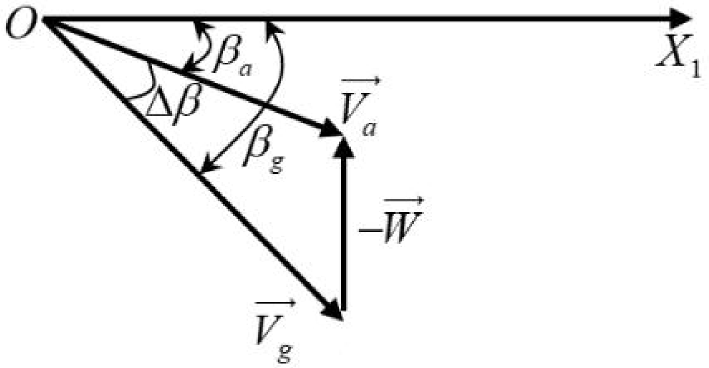

Figure 1. The relationship between velocity components and wind in the horizontal plane

The relationship between ground speed parameters and wind in the ground coordinate system, within the horizontal plane, is illustrated in the following diagram:

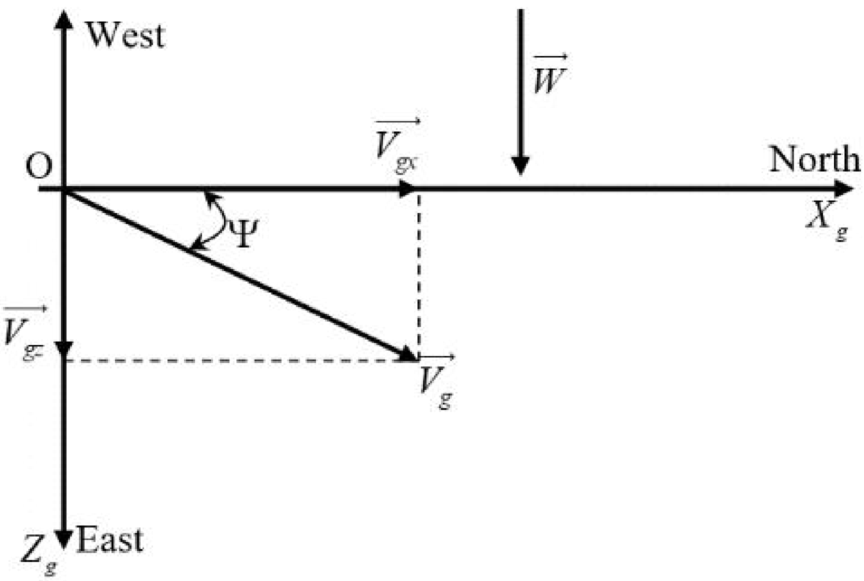

Figure 2. The relationship between ground speed components and wind in the ground coordinate system

By projecting the velocity components onto the coordinate axes, we obtain: $\begin{cases} V_{gx} = V_g \cos\Psi \\ V_{gy} = V_g \sin\Psi \end{cases}$

By projecting the wind components onto the coordinate axes, we obtain: $\begin{cases} W_x = 0 \\ V_z = W \end{cases}$

Thus, the airspeed components along the axes are calculated using the following equations: $\begin{cases} V_{ax} = V_g \cos\Psi \\ V_{ay} = V_g \sin\Psi - W_z \end{cases}$

Therefore $V_a = \sqrt{V_{ax}^2 + V_{ay}^2}$ and $\tan\beta_a = \frac{V_{az}}{V_{ax}}$

The angle between the airspeed and the ground speed is calculated using the following equation: $\cos(\Delta\beta) = \frac{V_g^2 + V_a^2 - W^2}{2V_g V_a}$

Therefore, the drift angle β_g is calculated using the following equation: $\beta_g = \beta_a + \Delta\beta$

Due to the UAV's aircraft-like characteristics, using yaw control based on the sideslip angle β to generate the lateral force Z_r is ineffective. Therefore, directional control during lateral motion employs the method of maintaining a roll angle $\gamma * \neq 0$ to produce a horizontal normal force $Y_r . \sin\gamma^*$ (Figure 3), which generates a turning rate $\frac{d\Psi}{dt}$. As a result, the flight direction Ψ and the lateral deviation z_o are controlled by generating and maintaining the roll angle $\gamma = \gamma *$.

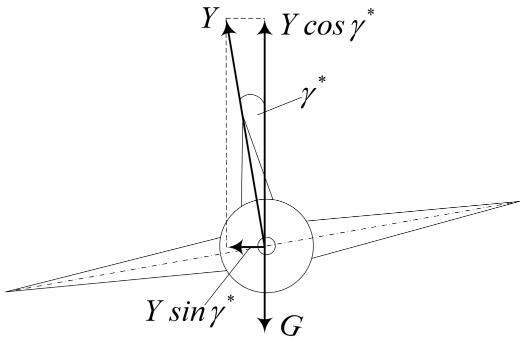

Figure 3. Directional control using roll angle

For UAVs, due to the inertia characteristics where $J_x << J_y$, the roll channel responds very quickly. Therefore, in lateral motion, it is assumed that the roll channel is stabilized and the desired roll angle $\gamma = \gamma *$ is always maintained. It is assumed that the control of the rudder and elevator surfaces is ideal. Consequently, the roll angle is used as a control signal, which is described by the following system of differential equations:

$$\begin{cases} -mV_g \frac{d\Psi}{dt} = Y_a . \sin\gamma^* + C_{z\beta} . \frac{\rho . V_a^2}{2} . S - T . \sin\beta \\ \frac{dx_o}{dt} = V_g \cos\Psi \\ \frac{dz_o}{dt} = V_g \sin\Psi \\ V_{ax} = V_g \cos\Psi \\ V_{ay} = V_g \sin\Psi - W_z \\ V_a = \sqrt{V_{ax}^2 + V_{ay}^2} \\ \tan\beta_a = \frac{V_{az}}{V_{ax}} \\ \cos(\Delta\beta) = \frac{V_g^2 + V_a^2 - W^2}{2V_g V_a}; \beta_g = \beta_a + \Delta\beta \end{cases} \tag{2}$$

Thus, to control the UAV's heading to the desired position, a PID controller is used, as expressed by the following equation:

$$\gamma^* = K_z . (z_o - z_{ct}) + K_{dz} . \frac{dz}{dt} + K_{iz} \int (z_o - z_{ct}) dt$$

However, it is observed that measuring lateral deviation speed using real-world measuring devices is very difficult. On the other hand, the corresponding relationship can only be measured by determining the heading angle Ψ ($\frac{dz_o}{dt} = V_g \sin\Psi$). Therefore, an algorithm to generate the desired roll angle is formulated, as expressed by the following equation:

$$\gamma^* = K_z . (z_o - z_{ct}) + K_\Psi . (\Psi - \Psi_{ct}) + K_{iz} \int (z_o - z_{ct}) dt \tag{3}$$

Where: z_o - the lateral deviation of the UAV; z_{ct}- the desired lateral deviation according to the flight plan (z_{ct}=0); ψ_{ct} - the desired trajectory heading angle (ψ_{ct}=0); The coefficients K_z,K_ψ,K_{iz},… are selected using the Simulink Response Optimization tool in Simulink.

To test the response capability of the control algorithm under crosswind conditions, it is assumed that the crosswind has a constant magnitude. The UAV model used is the UAV-70V [12], with the following technical parameters:

No.	Parameter	Value	Unit	No.	Parameter	Value	Unit
01	Length (l)	2707	mm	06	$m_z^{\omega_z}$	-16.23	[-]
02	Mass (m)	56.5	kg	07	$m_z^{\delta_c}$	-2.2144	1/rad
03	Height (h)	713	mm	08	m_z^{α}	-1.4798	1/rad
04	Wing area (S)	1.05	m^2	09	C_y^{α}	5.9123	1/rad
05	Wingspan (l_a)	3000	mm	10	$C_y^{\delta_c}$	0.6126	1/rad

Initial conditions of the landing process: $\begin{cases} h_0 = 60 \ (m) \\ x_0 = -1000 \quad (m) \\ v_a = 35 \ (m/s) \\ Z = 25 \quad (m) \\ \Psi = 0 \quad (rad) \end{cases}$;

Final conditions of the landing process: $\begin{cases} h_0 = 1 \ (m) \\ x_0 = 20 \quad (m) \\ v_a = 32 \ (m/s) \\ Z = 0 \quad (m) \\ \Psi = 0 \quad (rad) \end{cases}$

The values of the coefficients in the control law: $\begin{cases} K_z = 0.0637 \\ K_\Psi = 5.9 \\ K_{iz} = 0.003 \end{cases}$

The simulation diagram in MATLAB Simulink is illustrated in Figure 4.

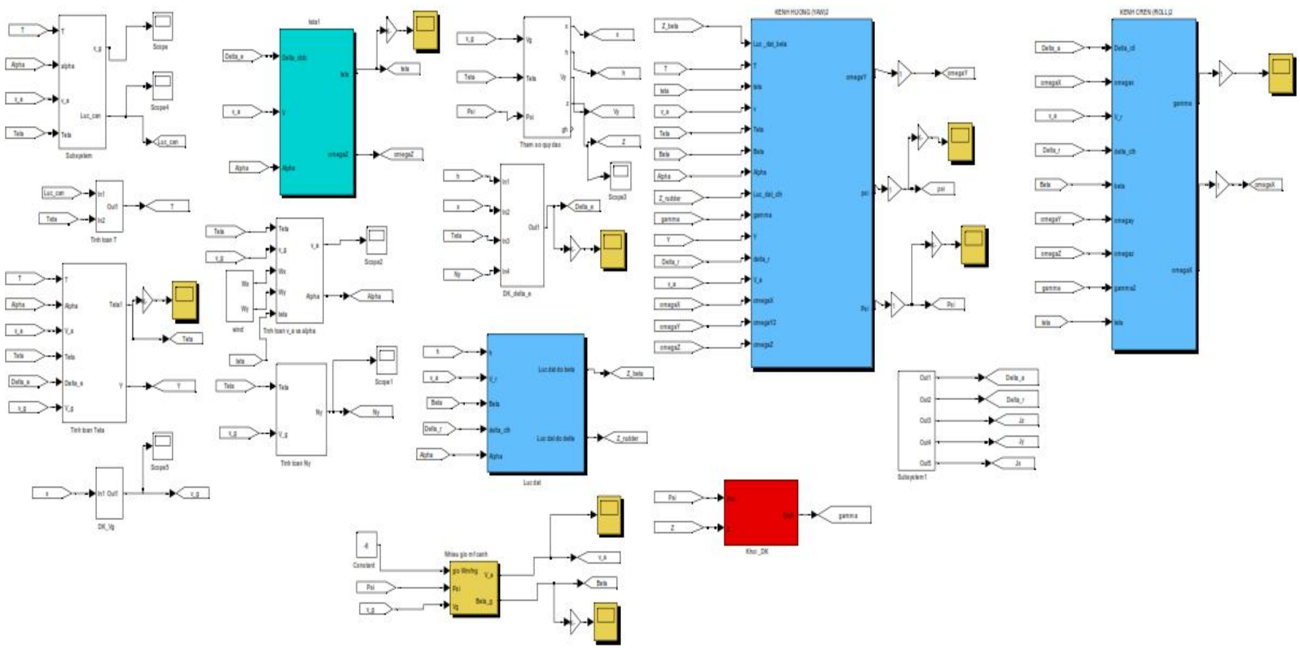

Figure 4. Simulation diagram in Matlab Simulink

The simulation results are presented in Figure 5.

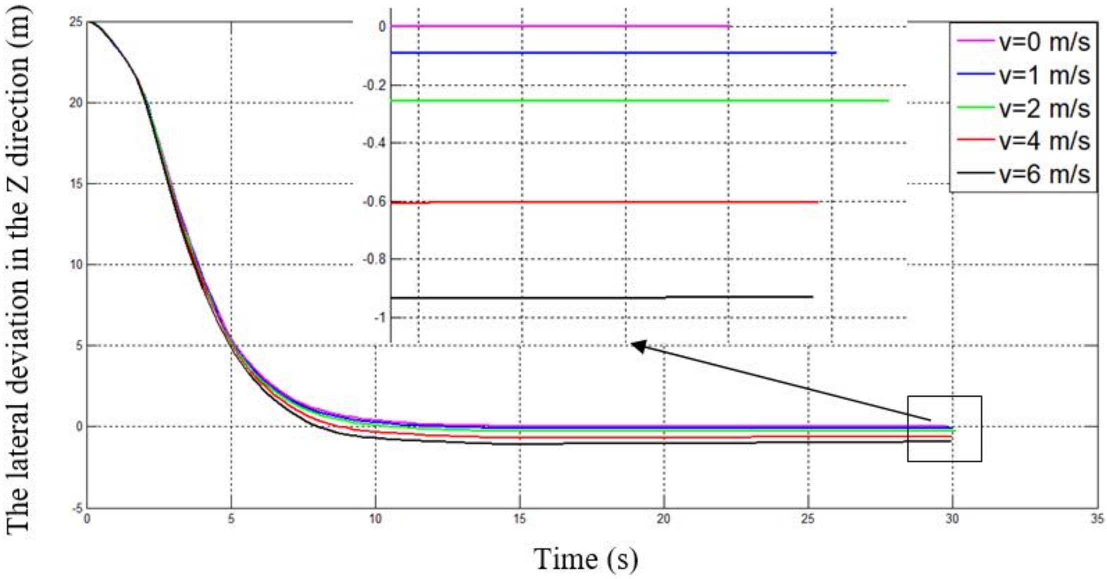

Figure 5. Simulation results of lateral deviation changes as crosswind varies

The landing process begins with a speed of 35 m/s and gradually decreases until touchdown. From the simulation results, it can be observed that when the crosswind changes, the automatic control system guides the UAV to the center of the airport. In the absence of crosswind, after approximately 10 seconds, the deviation control law brings the UAV to the airport center with almost zero error. As the crosswind magnitude increases, the control law shows that the static deviation at the final time increases. For a wind speed of 1 m/s, the final deviation is 0.1 m; similarly, for wind speeds of 2 m/s, 4 m/s, and 6 m/s, the lateral deviations are 0.22 m, 0.6 m, and 0.9 m, respectively. This error is relatively acceptable when considering the standards of the Federal Aviation Administration (FAA) [10]. According to these standards, the lateral deviation should be less than 4.1 m during the landing process.

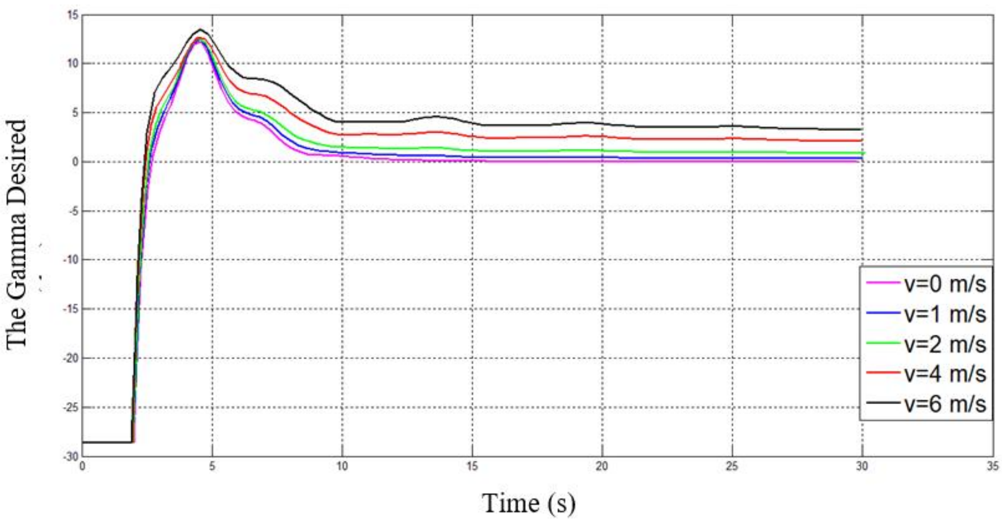

Figure 6. Desired gamma angle variation as crosswind changes

For the desired gamma angle parameter, in the absence of wind, the variation of this parameter meets the requirements of the automatic landing process, tending toward zero. However, as the wind increases, the deviations at the final time correspondingly increase.

Conclusion

The proposed UAV landing control algorithm in the crosswind plane basically meets the specified performance requirements, as defined by the standard [10]. Simulation results indicate that the crosswind deviation error at the final time remains within the permissible range, even when the lateral wind speed increases to 6 m/s, which demonstrates the robustness of the algorithm under moderate crosswind conditions. Furthermore, the desired flight path angle (gamma angle) consistently falls within the acceptable operational bounds, ensuring a safe and stable descent profile during the automatic landing phase. Despite these promising results, some limitations still exist. In particular, the presence of a small but noticeable static deviation at the final time suggests that the control system, while functional, may not fully eliminate steady-state errors under all wind conditions. To enhance the overall control quality and increase the reliability of the autonomous landing system, future work will focus on the application of advanced and modern control methods, such as adaptive control, robust control, or model predictive control (MPC) to effectively address more complex scenarios involving arbitrary and time-varying wind disturbances. The outcomes of this study serve not only as validation for the current algorithm's effectiveness but also as a benchmark for comparative evaluation in future research. In particular, the control performance achieved in this paper provides a reference point for assessing more sophisticated algorithms relative to the classical PID controller implemented in this study. This lays a solid foundation for future improvements in UAV autonomous landing systems, especially in the context of unpredictable environmental disturbances.

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