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Research Article

An investigation of the Control Quality of the Automatic Control System for Fixed-wing UAVs During Landing Process

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Abstract

This study presents an investigation and evaluation of the control quality of the automatic control system for UAVs in the vertical plane under windy conditions. For the operational stages of UAVs in general, the landing stage is one of the high-probability stages that pose a threat to flight safety, especially at the time of landing. Therefore, to evaluate the control quality of the system, the authors investigated the parameters during UAV landing. The automatic control system uses a PID controller with optimal parameters selected by the Signal Constraint tool in Matlab Simulink. The predetermined wind model was used to verify at the most extreme times. The programs proposed in the paper are simulated on Matlab Simulink software.

Keywords

UAV
PID controller
Automatic control system
Landing approach

Time Scale of Article

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1. Introduction

Today, unmanned aerial vehicles (UAVs) have increased popularity in the market, ranging from pure recreation to scientific research, making them broader and more comprehensive applicability areas. Therefore, control algorithms must be improved to increase flight safety and reliability.

While during flight conditions, the UAV is required to perform precise maneuvers and agile, during the landing process, the UAV should closely abide by a reference trajectory to obtain an efficient landing. A complete operational UAV consists of three stages: launching, mission flight, and recycling. The launching and mission flight stages are relatively mature thanks to advanced technologies, whereas recycling is still challenging for researchers (Tan et al., 2019). Besides, the autonomous control system for the landing process is a complex problem that needs more studies and research regarding both theory and implementations (Kim et al., 2016).

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Several methods have been developed and designed for automatic landing systems of UAVs, such as ground-based system (Kong et al., 2014), (Yang et al., 2016), fuzzy logic (Brukarczyk et al., 2021), hierarchical control structure (Zhang and Wang, 2017), neuro-adaptive (Ambati and Padhi, 2017), backstepping technique (Lungu, 2019), nonlinear model predictive control (Mathisen et al., 2020), combination for low-level control architecture (Manjarrez, Davila and Lozano, 2018).

In the literature, various papers give interesting approaches to landing trajectory optimization, including fuzzy logic (Magnus, 2016), deep reinforcement learning (Bayerlein, Kerret and Gesbert, 2018), solving the system of differential motion of UAV to determine the desired landing orbit (Rohacs and Dung, 2019), artificial neural network (Moriarty, Sheehy and Doody, 2017). Yi Feng et al. developed a predictive model controller for UAVs in the landing process under varied turbulence, which guarantees a safe and accurate flight (Feng et al., 2018). In contrast, Sanches-Lopez et al. combined the Kalman filter with a vision for improving an autonomous landing algorithm (Sanchez-Lopez et al., 2013). T. Yang et Al. presented an infrared camera array guidance system to track and give a UAV's real-time position and speed during the landing process (Yang et al., 2016). Such a system used two infrared cameras and a laser lamp: a laser lamp was fixed on the nose to calculate the position. Two infrared cameras were located on the two sides of the runway to capture flying UAV images. Based on this information, the real-time position and speed of the UAV were calculated and sent to the UAV control center.

The landing control issue can be divided into two categories: control and guidance. At the low-level, attitude control is a precondition for the landing process, which can apply sliding mode control (Venkateswara Rao and Go, 2014) and backstepping techniques (Lungu, 2019). At the middle level, proportion integration differentiation (PID)-based controllers are designed to determine the desired attitude. At the same time, a proportional guidance law is designed for height tracking at the top level. Besides, guidance laws are designed based on attitude control, based on the linear model (Wang and Wen, 2010), nonlinear energy method (Jones, Akmeliawati and Tan, 2010), fuzzy logic modules (Brukarczyk et al., 2021), a linear quadratic tracker with integral (Koo, Kim and Suk, 2015), and nonlinear model predictive control (Mathisen et al., 2020). However, most of the abovementioned approaches require exact knowledge of system parameters and validation of the performance using numerical simulations.

In recent years, the research and manufacture of UAVs have also made significant progress. An onboard edge motion controller was synthesized for unmanned aerial vehicles (UAV) under some simple conditions (Quang, 2008), (Dang et al., 2016). For the problem of trajectory and tracking, P. Anh et al. proposed tracking algorithms for UAVs, such as a virtual line of sight algorithm, based on sliding mode (Thi, Nguyen and Phan, 2018). That study indicated that the navigation algorithm based on the sliding mode, the system is stable quickly and can be proposed to be used for all different modes. Taking into account the control signal limitation, Toan et al. presented a method to optimize the landing trajectory for autonomous fixed-wing UAVs by applying the Pontryagin maximal principle (Ngo et al., 2019). An investigation of the PI controller for autonomous fixed-wing UAV in the vertical plane with no wind conditions was presented (Ngo et al., 2020). Considering wind disturbance, Vu et al. developed a gradient speed adaptive controller with an explicit reference model (Dang et al., 2016). Thu et al. proposed a method to determine the parameters of the UAV to serve the landing process, including pitch angle, inclination angle, direction angle, distance, angle deviation, and the height of the UAV (Do, Do and Ngo, 2016). These parameters are used to control the UAV tracking the landing trajectory safely. However, these works are still relatively modest in terms of the quality and size of the problem. Conventional studies only deal with a relatively minor aspect with given hypothetical conditions and do not come close to the actual flying conditions of the UAV. To overcome this issue, an improvement of the automatic control system for fixed-wing UAVs was presented in the previous works (Tran et al., 2022). Although this improvement was sastified by the numerical simulation results, some limitations of that study still existed, including the UAV speed was set to be constant during landing process; the UAV motion was not considered in the landing approach; the UAV's altitude was slightly higher than the actual operation of the UAV-70.

Therefore, this study investigates the controller quality for fixed-wing UAVs under windy disturbances, making the research results more closely related to the actual conditions.

2. Methods

In this study, the motion of UAVs will be taken into the synthesizing the control rule for the autonomous control system. The following equation system describes the kinematic model of the UAV (Ngo et al., 2020):

Where, V_g– ground speed; V_a– air speed; m – mass of UAV; α - attack angle; θ - flight path angle; x – distance of the flight; y – heigh of the flight; C_D- drag coefficient; C_L- lift coefficient; ρ- air density.

$$\begin{cases} m\left(\frac{dV_g}{dt}\right) = T\cos\alpha - C_D.\alpha\frac{\rho.V_a^2}{2}.S - G\sin\theta \\ mV_g\frac{d\theta}{dt} = T\sin\alpha + \left(C_L.\alpha + C_y^{\delta_e}.\delta_e\right).\frac{\rho.V_a^2}{2}.S - G\cos\theta \\ J_z\left(\frac{d\omega_z}{dt}\right) = \left(m_z^{\delta_e}.\delta_e + m_z^{\alpha}\alpha\right).\frac{\rho.V_a^2}{2}.S.b_a \\ \frac{dx_o}{dt} = V_g\cos\theta \\ \frac{dy_o}{dt} = V_g\sin\theta \\ \frac{d\vartheta}{dt} = \omega_z \end{cases} \quad (1)$$

The motion of UAVs is considered in the landing process that measures from the beginning to a grounding point. After practicing with UAV-70 in the natural environment, we recommend that the length of the landing trajectory is around 1000m, and the heigh of the beginning point is around 60m. The grounding point is based on the UAV's structural properties, safety, and flight accuracy. Therefore, in this study, we assume that (i) the grounding point is 20m from the head of the runway, and (ii) the reference trajectory is a parabolic sharp. Figures 1 and 2 describe the UAV's reference trajectory and flight path angle during the landing process.

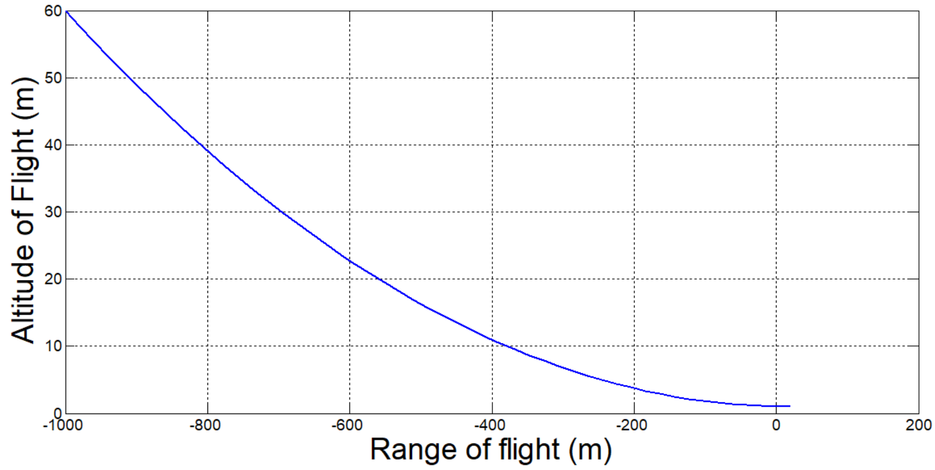

Fig. 1. UAV landing reference trajectory

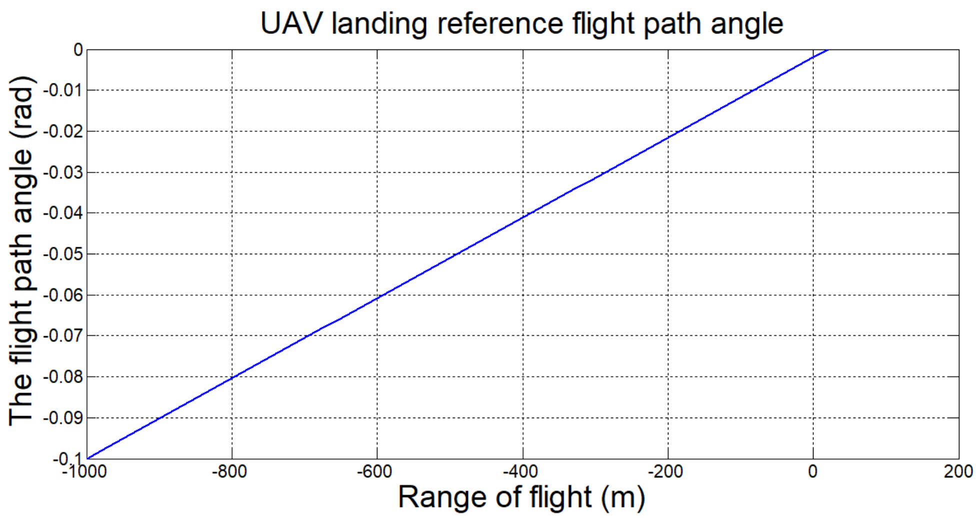

Fig. 2. UAV landing reference flight path angle

The following equation system is calculated based on the geometrical parameters, illustrating the reference trajectory of the UAV.

$$\begin{cases} h = \frac{59}{1040400}x^2 - \frac{59}{26010}x + \frac{2660}{2610} \\ \theta = \frac{1}{10200}x - \frac{1}{510} \end{cases} \quad (2)$$

The author proposes using the PID controller, a powerful method in this study. The parameters of the autonomous control system (K_p, K_i, K_d) were optimized by the tool "Signal Constraint" in the "Simulink Design Optimization" in the Matlab software.

Whereas, if both the heigh error and flight path angle are reached zero, the PID controller will be well done. Therefore, we propose the control law in the vertical plane, described in equation (3), by which the UAV will follow the reference trajectory.

$$\delta_e = K_p\Delta h + K_d\Delta\theta + K_i\int_0^t \Delta h dt + \delta_{e\_bb} \quad (3)$$

Where, $\Delta h = h_{cur} - h_{ref}$: heigh error (m)

h_{cur} : Current heigh (m);

h_{ref} : Reference heigh (m);
$\Delta\theta = \theta_{cur} - \theta_{ref}$: Flight path angle error (rad);
θ_{cur} : Current flight path angle (rad);
θ_{ref} : Reference flight path angle (rad);
K_p : Proportional coefficient (rad/m);
K_d : Derivative coefficient (-);
K_i : Integral coefficient (rad/m);
δ_{e_bb} : Starting elevator deflection angle (rad);

We synthesize a closed loop based on the rule (3) for vertical channel, usisng PID controller during landing process.

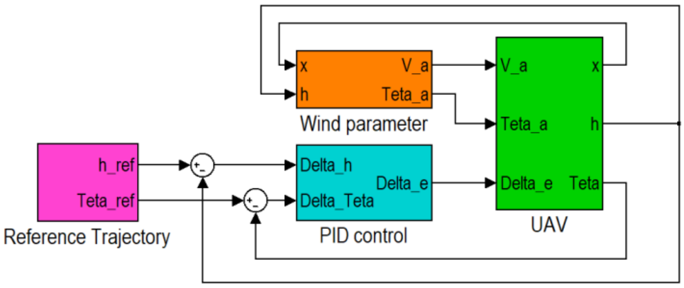

Fig. 3. The UAV control system in the vertical plane.

When the UAV is grounded, the following conditions must be met:

- Range of flight error from the head of the runway $|\Delta x| \le 30m$;
- Altitude error at the touching point $0m \le |\Delta h| \le 0{,}3m$;
- Touching speed $V_{hc} \ge V_{min}$ (where $V_{min} = \sqrt{\frac{2G}{C_{yHC}\rho S}}$)
- Vertical speed $|V_y| \le 1m/s$;
- Pitch angle at the grounding point $0 \le \vartheta \le 12°$;

3. Simulation Results and Discussion

The First Case

We used parameter of UAV-70 (Ngo *et al.*, 2020) in this study. UAV motion in case tailwind maximum parameters: $L = 14\ (m);\ W_0 = 6\ \left(\frac{m}{s}\right);$

Initial state of UAV: $\begin{cases} h_0 = 60\ (m) \\ x_0 = -1000\ (m) \\ v_g = 40\ (m/s) \end{cases};$

Final state of UAV: $\begin{cases} h_t = 1\ (m) \\ x_t = 20\ (m) \\ v_y = 0\ (m/s) \\ v_g = 32 (m/s) \end{cases};$

PID parameters: $\begin{cases} K_p = 0{,}0111 \\ K_d = -0{,}2514 \\ K_i = 0.0029 \end{cases}$

The simulation results are shown in Figures 4-5

The parameters of the UAV at the time of grounding point are given in table 1 as follows.

The Second Case

Simulation results for the case compare four different conditions at touching down.

To further test the effectiveness of the PID controller, the authors use four extreme wind models at the time of touching down of the UAV. It is assumed that the mode of the UAV motion velocity vector, $V_a(t)$, is known constant during the UAV landing approach. For the UAV landing time, the predicted position of the UAV is $P(x_t, h_t)$. The numerical simulation results are shown in figures 6-12.

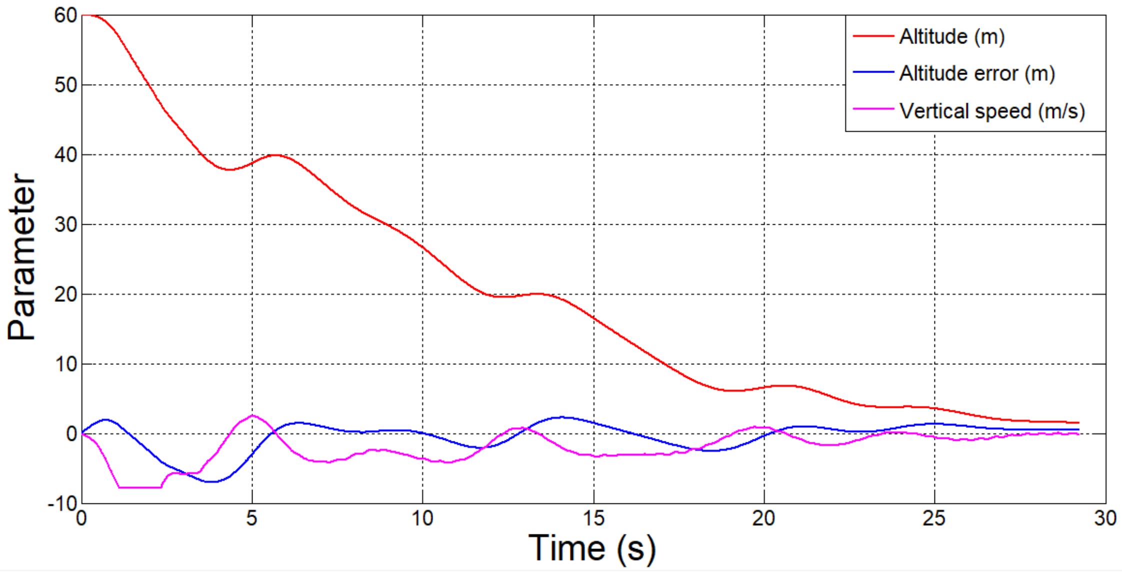

Fig. 4. The UAV's parameter-1

Table 1. Parameters of UAV at the time of grounding point.

Section No	Parameter	Value	Permissible value	Value from (Ngo *et al.*, 2020)
01	Altitude error	$\Delta h = 0.09$ m	$\lvert\Delta h\rvert \leq 0.3$	$\Delta h = 0.12$m
02	Range of flight error	$\Delta x = 0.2$ m	$\lvert\Delta x\rvert \leq 30$	$\Delta x = 0.3$m
03	Vertical speed	$\lvert V_y\rvert = 0.3$ m/s	$\lvert V_y\rvert \leq 1$	
04	Pitch angle	$\vartheta = 7^o$	$0 \leq \vartheta \leq 12^o$	$\vartheta = 10^o$

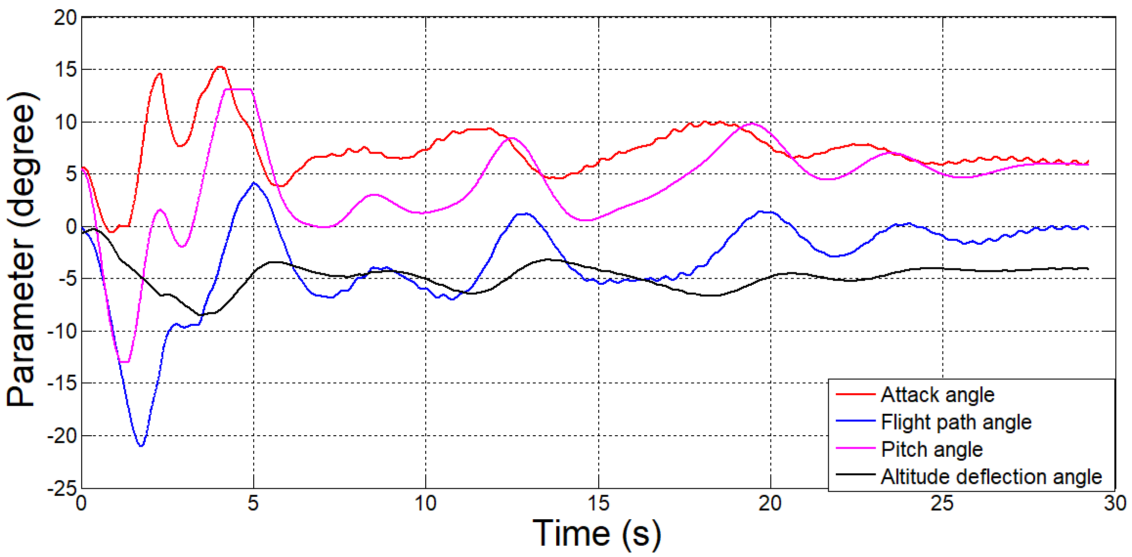

Fig. 5. The UAV's parameter-2

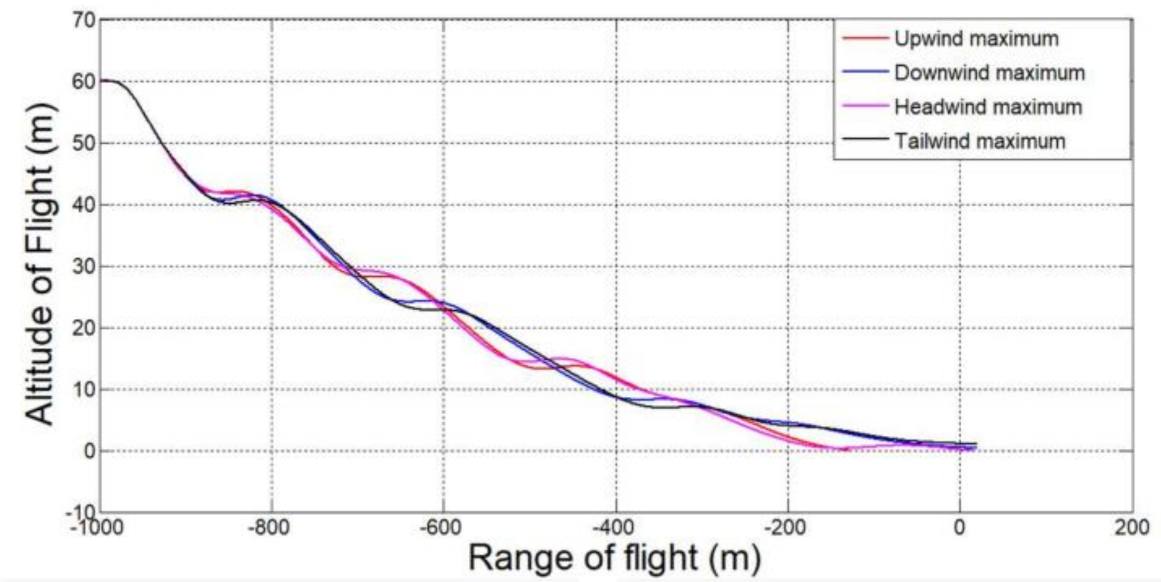

Fig. 6. The UAV's trajectory

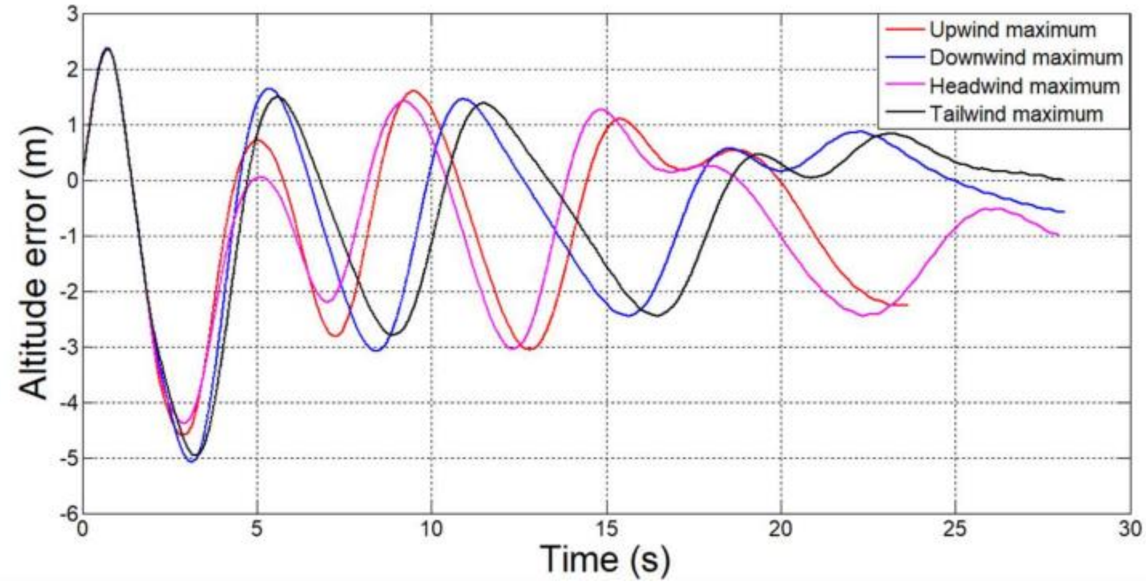

Fig. 7. The altitude error

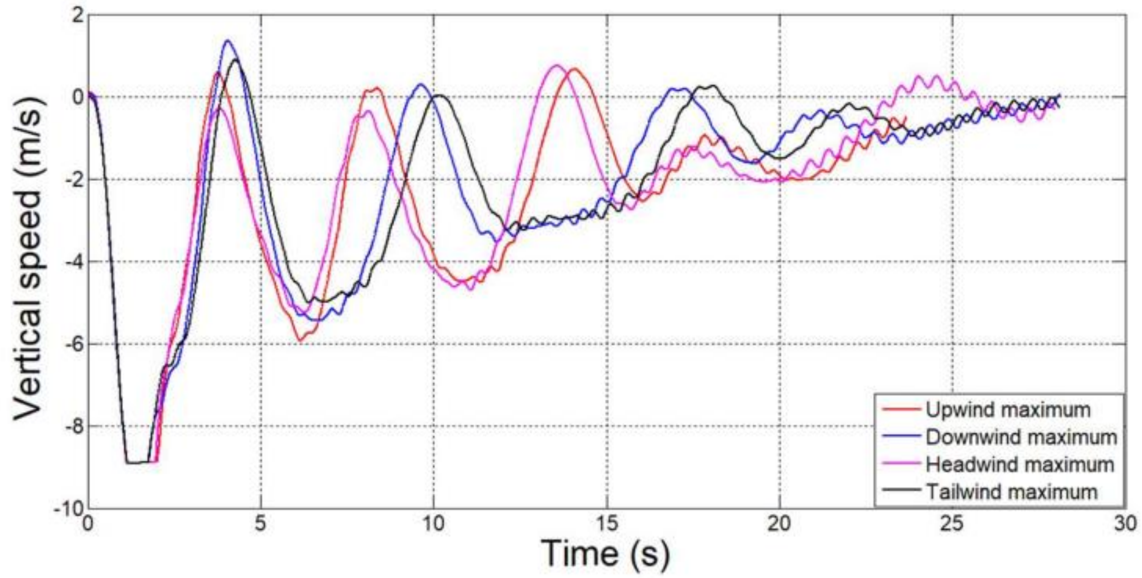

Fig. 8. The vertical speed

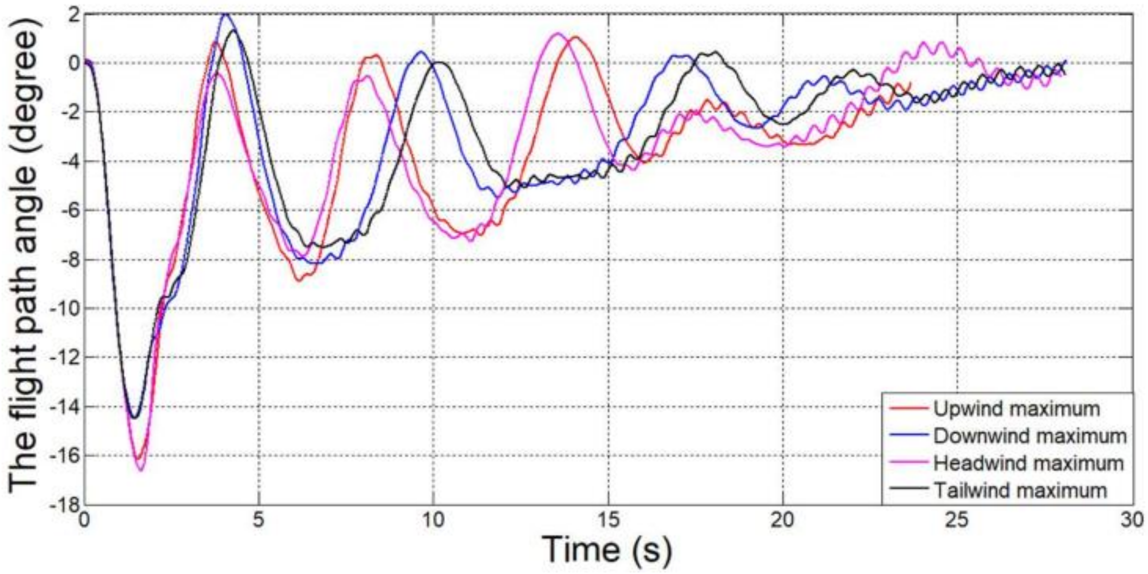

Fig. 9. The flight path angle

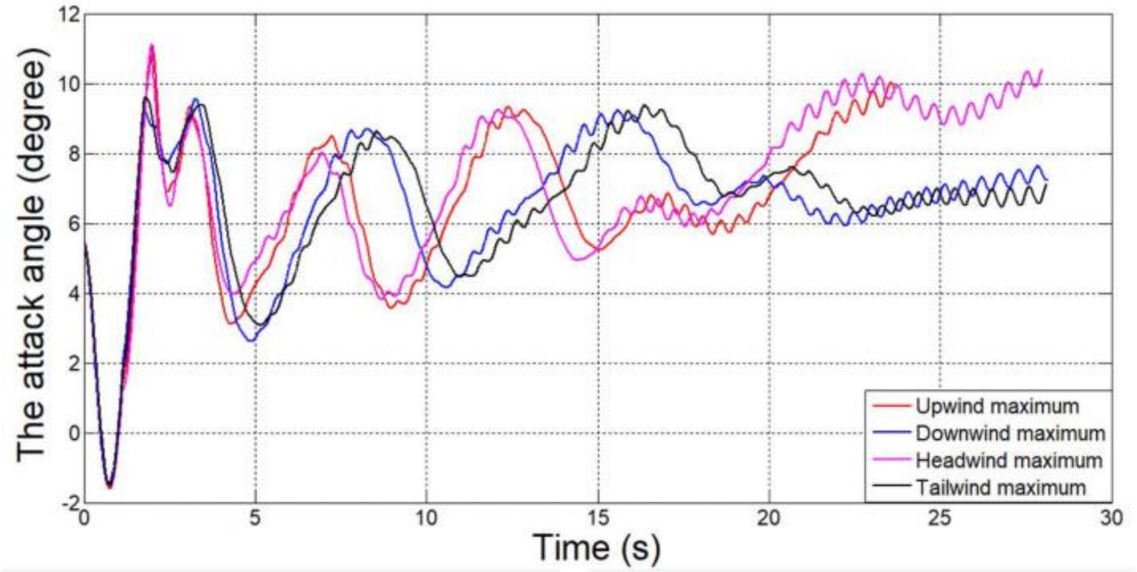

Fig. 10. The attack angle

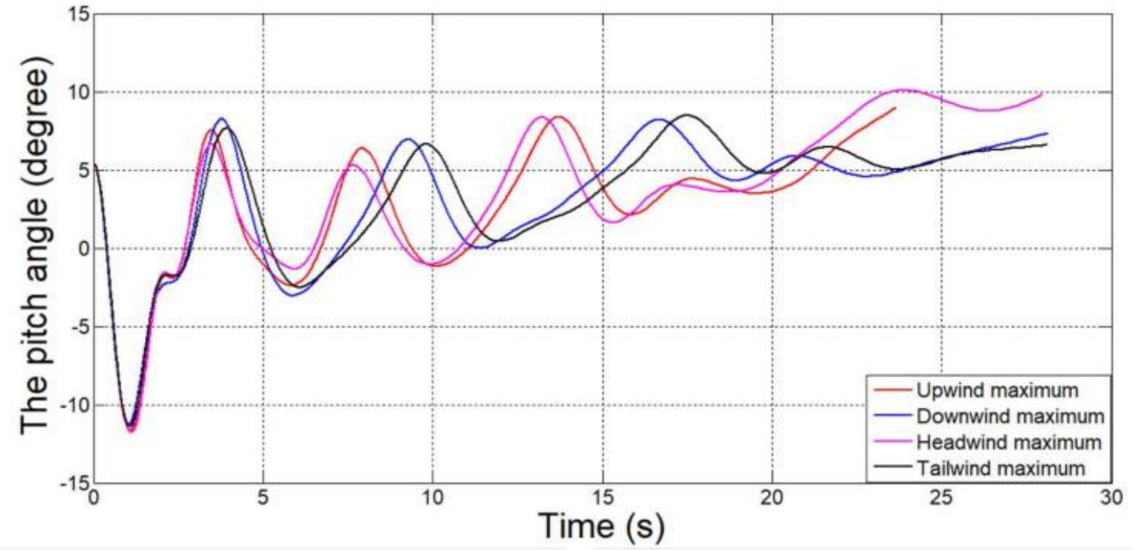

Fig. 11. The pitch angle

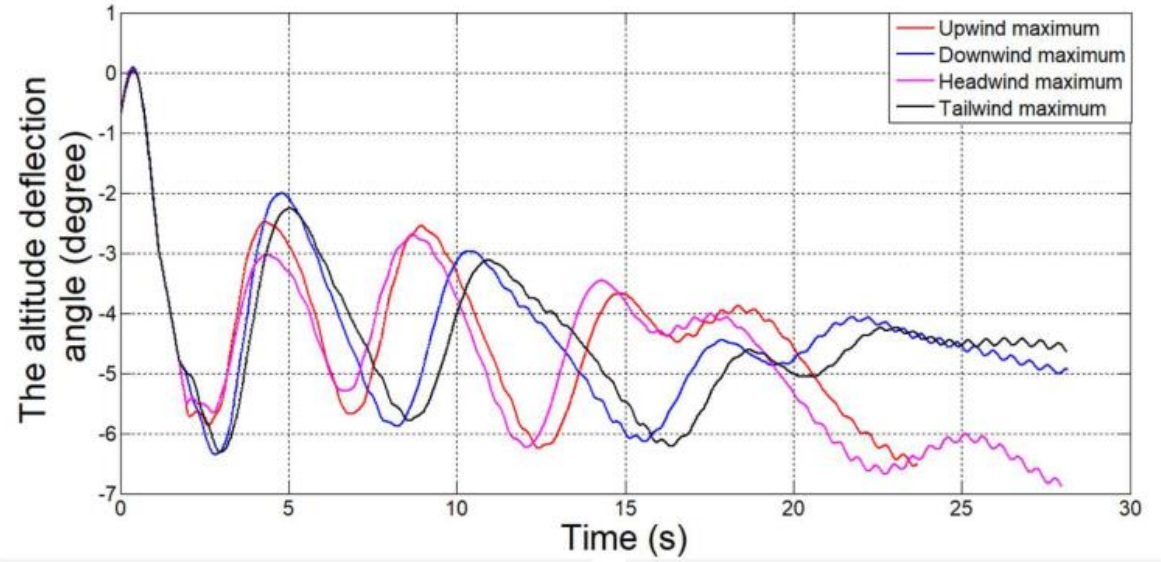

Fig. 12. The altitude deflection angle

4. Conclusions

In this study, the authors investigate and evaluate the control quality of the automatic control system for fixed-wing UAVs in the vertical plane with wind conditions. The automated control system used a PID controller with optimal parameters with a predetermined wind model. The comparison of the proposed approach with the system-used PI controller and previous work also are given in this paper, indicating that the quality of the proposed PID controller is much more effective than the results of the PI controller with wind conditions in the vertical plane. Although some parts of the previous study have been overcome, the proposed PID controller's errors during the landing stage still exist. While this paper investigated the automatic landing system of UAVs in the vertical plane, future research will expand this work to complete the problem of UAV landing in space, such as investigating this system within wind disturbance.

Abbreviations

UAV : Unmanned Aerial Vehicle
PID : Proportion Integral Derivation
PI : Proportion Integral

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