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Research Article

High Precision Height Control for Wing-in-Ground Crafts

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The wing-in-ground effect craft (WIG craft) is a kind of vehicle that flies close to the ground to achieve a flight with low aerodynamic drag and high lift. A robust and precise height control system is essential to ensure small WIG crafts fly safely in ground effect. In this paper, the performance of different high precision height control systems based on PID controllers is investigated numerically with different altitude disturbances. The results show that a control system that operates throttle, elevators, and flaps to control the altitude of the aircraft (TPF control system) results in the minimum overshoot, undershoot, rising tine, and settling time recovering from a disturbed altitude, with fluctuation in pitch angle. Compared to the TPF control system, even though the control system that operates throttle and flaps (TF control system) has a longer settling time and a higher overshoot, it has a smaller oscillation in pitch angle during a disturbed altitude. In addition, operating the throttle helps reduce the change of flight velocity during altitude disturbance. Furthermore, simulation results based on the TPF control system, show that the ground effect has little influence on the performance of control systems.

1. Introduction

The ground effect is an aerodynamic effect that allows the wing to gain an additional increase in lift and decrease in drag when flying close to the ground or water (usually at an altitude not exceeding the chord length of the wing) [1]. A wing-in-ground effect craft (WIG craft) is a delivery vehicle with an excellent ultralow altitude cruise capability that utilizes the ground effect principle to fly. In comparison with general aircraft and ships, WIG crafts have the advantages of higher transportation efficiency, faster maneuverability, and improved economy. For these reasons, they have broad application prospects. WIG crafts could be used to patrol coastal waters and assist the islands' transportation infrastructure, such as transferring passengers and freight. In addition, WIG crafts can be employed as rescue vehicles in the event of an emergency. According to an analysis of available sea rescue methods, surface ships cannot reach the accident site quickly enough, and helicopters cannot undertake effective rescue operations because they cannot land close enough to the sinking ship [2].

Automatic altitude control is a crucial part of managing the motion and preserving the stability of WIG craft because it is designed to cruise at low height over sea waves to avoid collision. Compared with typical aircraft, WIG crafts' longitudinal stability is affected not only by their pitch angles but also by their relative altitude over the water surfaces [3]. In addition, compared with large WIG crafts, small WIG crafts are more sensitive to wave disturbance because they have to fly closer to surfaces to utilize the ground effect. Therefore, it is necessary to construct a high precision height control system to ensure small unmanned WIG crafts cruise at a precise altitude and their stability.

WIG crafts have existed for decades and several different WIG crafts have been designed and built in the past years. Nevertheless, most of the research published in journals focuses on the flight stability of large WIG crafts, while the ground effect phenomenon on small WIG crafts especially their longitudinal stability has not been virtually explored. Qu et al. [4] found that the aerodynamic forces are periodic when the WIG crafts flew over the wavy ground and under the condition of the angle of attack $\alpha = 9^\circ$, and a decrease in height would eventually result in flow separation. Qu et al. [5] solved the compressible Reynolds-averaged Navier-Stokes equations and shear-stress transport $k-\omega$ turbulence model equations by finite-volume method to investigate the aerodynamics and flowfield of a NACA 4412 airfoil near the flat ground for angles of attack

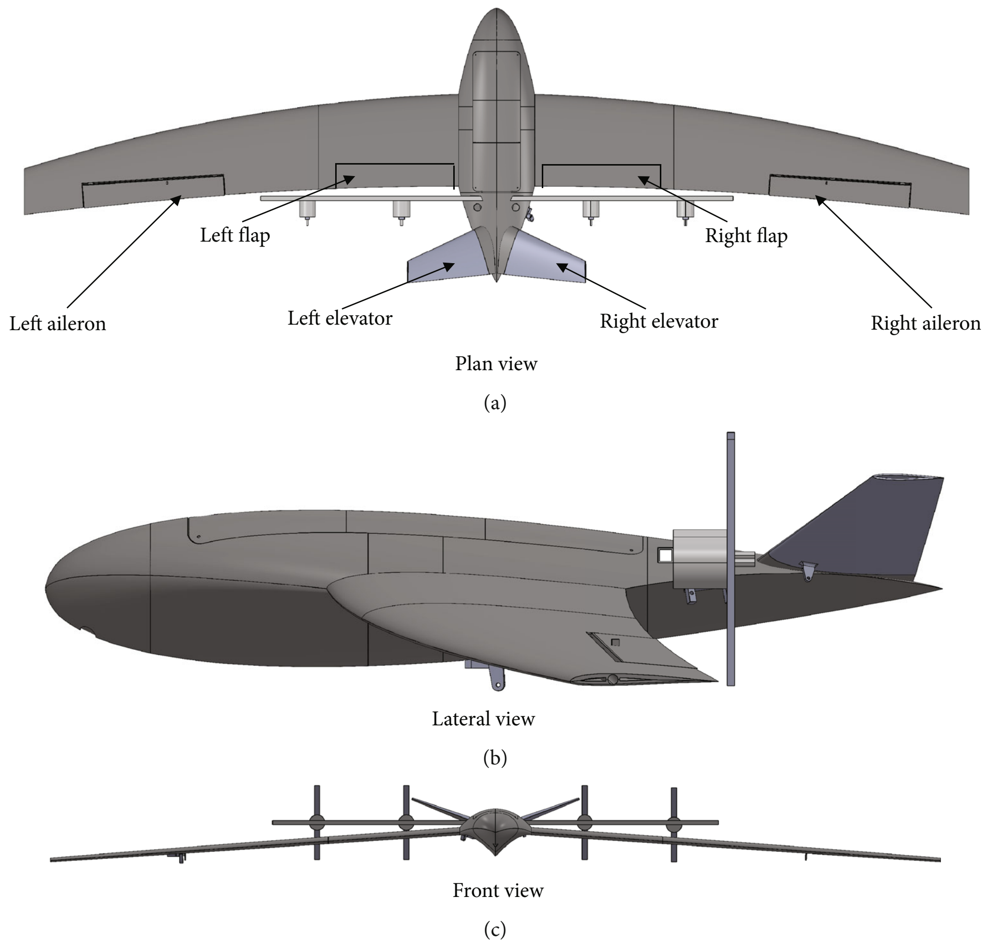


Figure 1: View of Aero-WIG testing vehicle. (a) Plan view. (b) Lateral view. (c) Front view.

Table 1: Basic parameters of Aero-WIG.

Basic parameters of Aero-WIG	Value
MTOW (kg)	4.0
Span (m)	2.0
Length (m)	0.6
Reference wing area (m^2)	0.34
Reference chord (m)	0.2
Propeller diameter (inch)	7
Tail volume ratio	0.14
AC (from the nose, m)	0.268
CG	0.255

from -4 to 20 degrees. They found that based on the sign of the lift increment value, the angle of attack versus height above the ground can be separated into three regions: one region of positive ground effect and the other two regions of negative ground effect.

Similarly, few studies focused on the design of control systems for WIG crafts. Nebylov and Nebylov [6–11] discussed some vital problems of automatic control of WIG-effect crafts: precision devices developed for modern means of automatic control and control algorithms. They considered the accuracy and reliability of flight parameters measured by modern sensors and pointed out that for a particular WIG craft, the concept of flight control needed careful consideration as well as the control algorithms required special research and design. In addition, a majority of studies of flight control for conventional small fixed-wing aircraft focus on attitude and altitude control in the presence of external disturbance caused by wind, failing to give sufficient consideration to the influence of ground effect [12–18]. Akyurek et al. [13] developed an autopilot system containing an inner loop and outer loop for small fixed-wing aircraft. The inner loop used the H_∞ loop shaping method to provide the stabilizer and the outer loop used a PID controller to provide motion controls such as speed, direction, and altitude. Zhai et al. [18] employed traditional linear PID for longitudinal control to achieve altitude control and used a nonlinear control method for lateral control which could adapt to changes in ground velocity caused by gust disturbance. Trilaksono et al. [17] designed a PID controller with the Ziegler-Nichols tuning method for longitudinal mode and lateral directional mode, improving response time characteristics of UAV. Melkou et al. [16] proposed a control system based on a second-order sliding mode (SOMO) control which could overcome external disturbance, ensure rapid convergence, and gain adaptation reduced chatter especially. Ahsan et al. [12] compared PID controller with phase lead compensator and found that phase lead

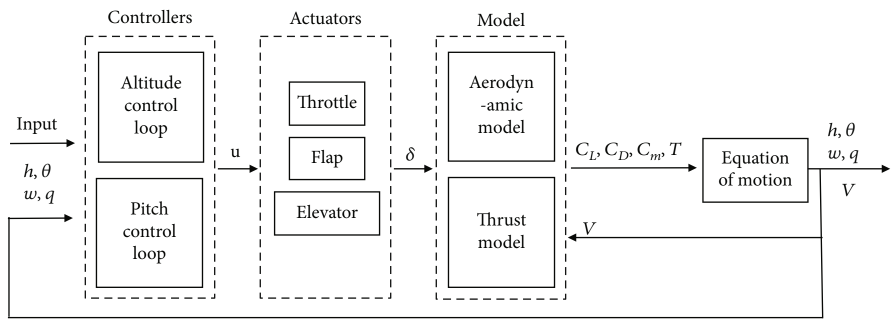


Figure 2: Structure of control model.

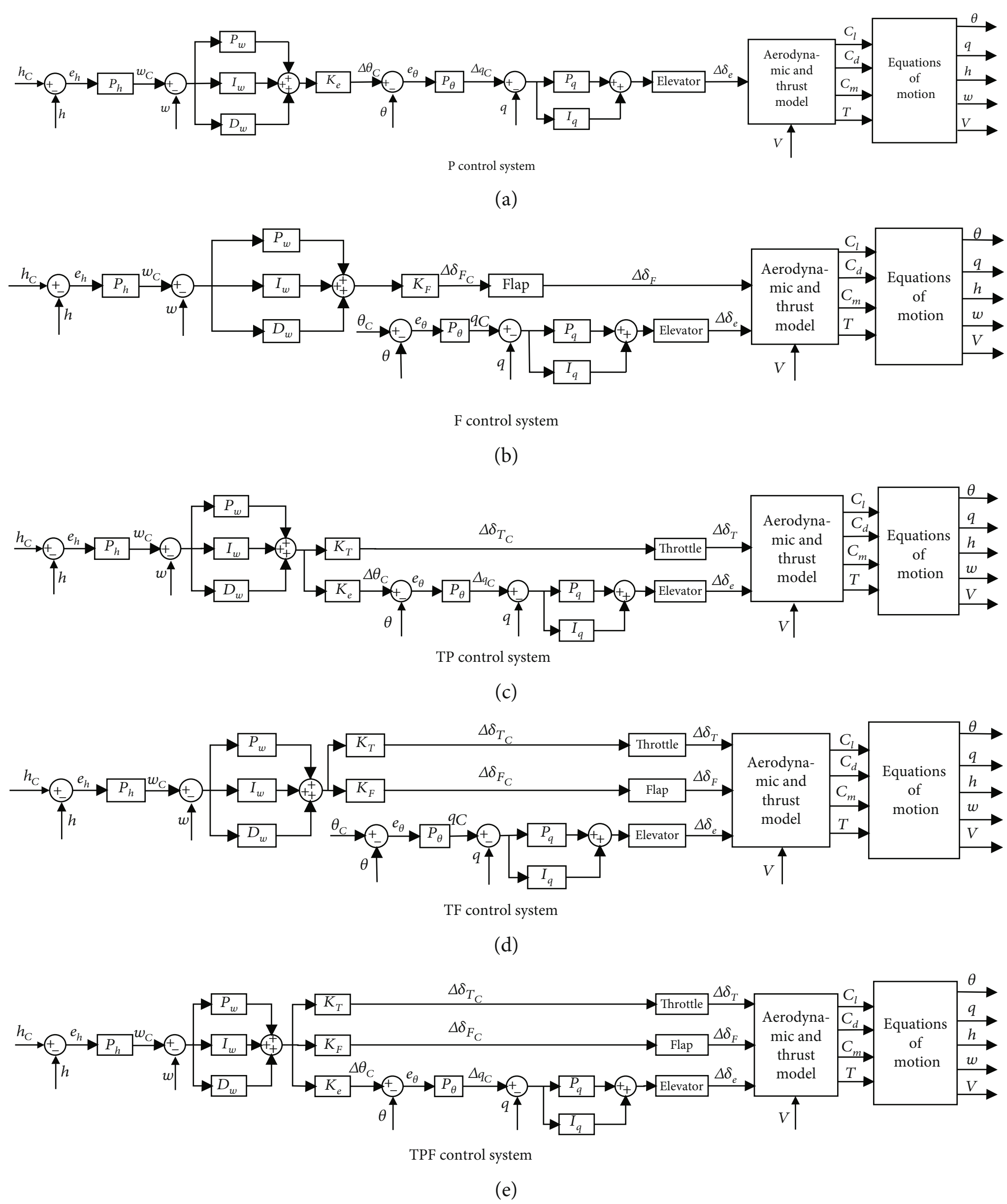


Figure 3: Structures of different height control systems. (a) P control system. (b) F control system. (c) TP control system. (d) TF control system. (e) TPF control system.

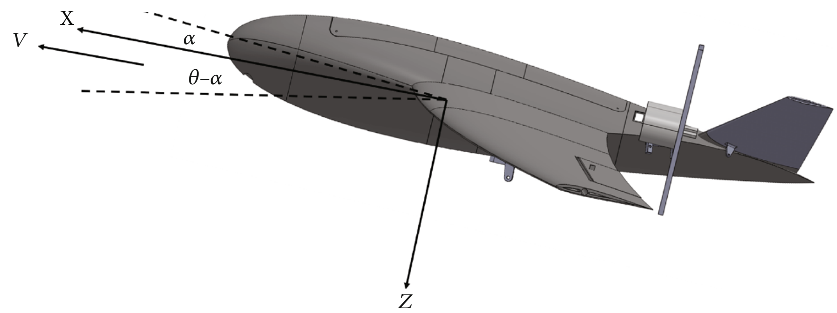


Figure 4: Longitudinal motion of Aero-WIG in wind axes.

Table 2: Results of different control systems recovering from a 1 m disturbed altitude (ascent).

Control systems	t_r	$t_{S,2\%}$	Overshoot
F	0.36 s	1.32 s	6.02%
P	0.25 s	1.55 s	17.89%
TF	0.34 s	1.30s	6.28%
TP	0.23 s	1.52 s	18.13%
TPF	0.27 s	0.86 s	4.45%

Table 3: Results of different control systems recovering from a 1 m disturbed altitude (descent).

Control systems	t_r	$t_{S,2\%}$	Undershoot
F	0.36 s	1.68 s	13.41%
P	0.26 s	2.13 s	31.35%
TF	0.35 s	1.67 s	13.76%
TP	0.25 s	2.14 s	32.02%
TPF	0.28 s	1.42 s	9.39%

compensator had a faster transient response and smaller overshoots. Hernandez and González-Hernández [15] compared the PID controller with the nonlinear controller by simulation. They found that in the use of stabilizing UAV's attitude and altitude, only a linear control system was enough for the roll angle control, while in the cases of the other two attitude control and altitude control, PID had better results. Ji et al. [19] established a 6-DOF mathematical model for WIG crafts and designed a control system using a PID controller to control the attitude and altitude. The simulation results verified the effectiveness of the control system. Patria et al. [20] compared the performance of different nonlinear control strategies (MPC, PID, and LQR) in simulation and got the conclusion that LQR performed the best overall.

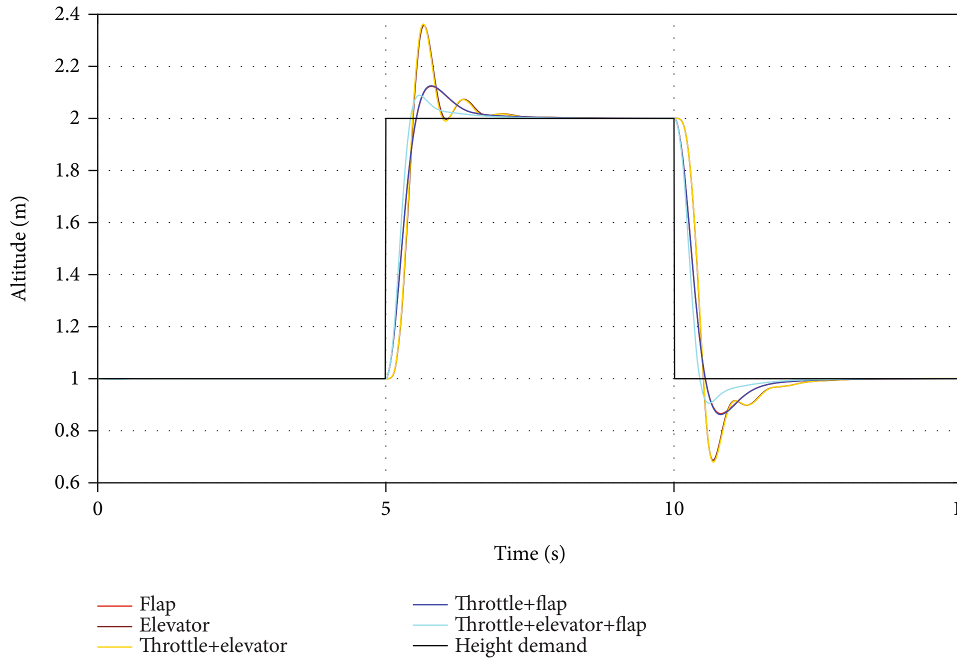
In this paper, different closed-loop precise altitude control systems based on PID controllers are constructed for a small WIG craft. The performance of different control systems is tested and compared in MATLAB simulations. Section 2 gives the details of the model of the small WIG craft (Aero-WIG), longitudinal equation of motion, and the design of different high precision height control systems. In Section 3, simulation results of flight controllers are presented. Finally, the paper is concluded in Section 4.

2. Height Stability Simulation and Control Algorithm

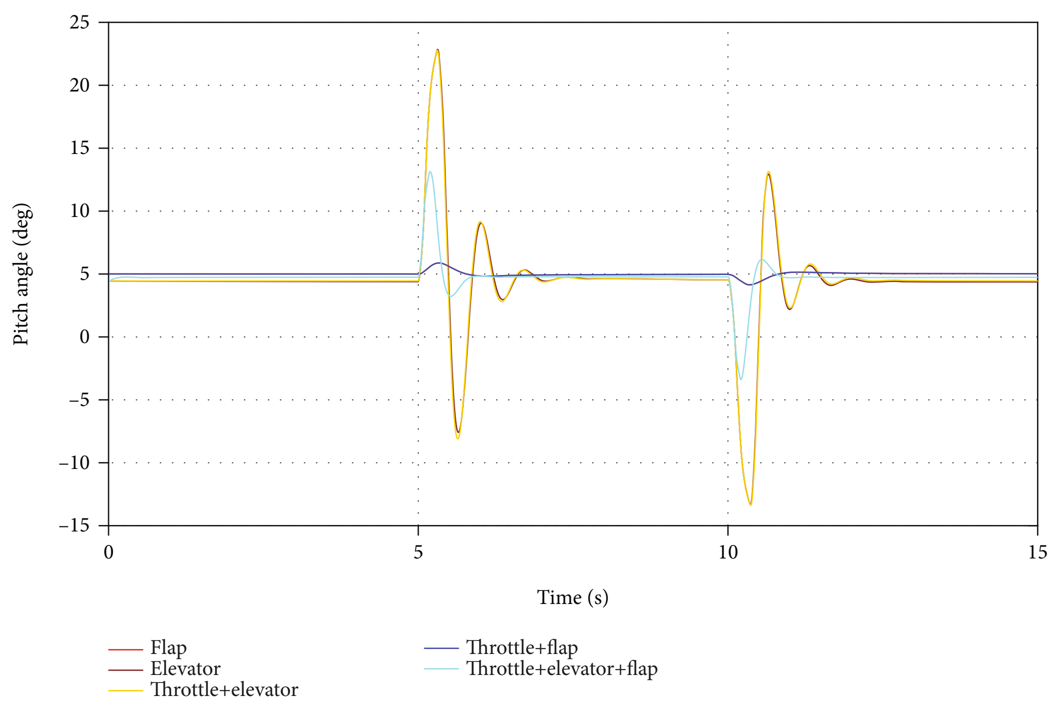
2.1. The Aero-WIG Testing Vehicle. As shown in Figure 1, the Aero-WIG testing vehicle is composed of a fuselage, a wing (including a central wing, two flaps, and two ailerons), four motors, and a pair of V elevators. The basic parameters of Aero-WIG are shown in Table 1.

2.2. Stability Simulation and Control Modeling. The whole control flow of the control model is shown in Figure 2. If the reference input differs from the state parameters of the aircraft (h, θ, w, q), the controllers will process the error and generate control signals u to actuators to control angles of control surfaces and speed of propellers. With information from actuators (δ) and equation of motion, the aerodynamic parameters of aircraft $C_l, C_d,$ and C_m and thrust of propellers T can be obtained. Then, the state of the aircraft can be calculated by solving equations of motion with the parameters.

The precise height control system can be divided into an attitude control loop and an altitude control loop based on PID controllers. A mixer of P and PI controller is employed to control the attitude of the Aero-WIG by controlling the angles of elevators, and a mixer of P and PID controller is used to control the speed of motors and degrees of flaps to complete altitude hold mode. The structure of the altitude/attitude control loop, and different height control algorithms are shown in Figure 3. In the altitude control loop, with reference height control signal h_c minus the aircraft's height h, the height error e_h can be obtained. Then, e_h is transformed to reference velocity control signal w_c by the P controller. Similarly, with w_c and the aircraft's velocity in z axes w processed by the PID controller, the altitude control loop generates control signals. Likewise, attitude (pitch) control loop processes reference pitch angle input, aircraft's pitch angle, and angle rate with the P-PI controller. Figures 3(a), 3(c), and 3(e) depict the structures of height control systems that combine the attitude control loop and the altitude control loop in series, namely, the P control system, TP control system, and TPF control system. In these control systems, the attitude control loop receives pitch angle control signals $\Delta \theta_c$ from altitude control loop and operates elevators

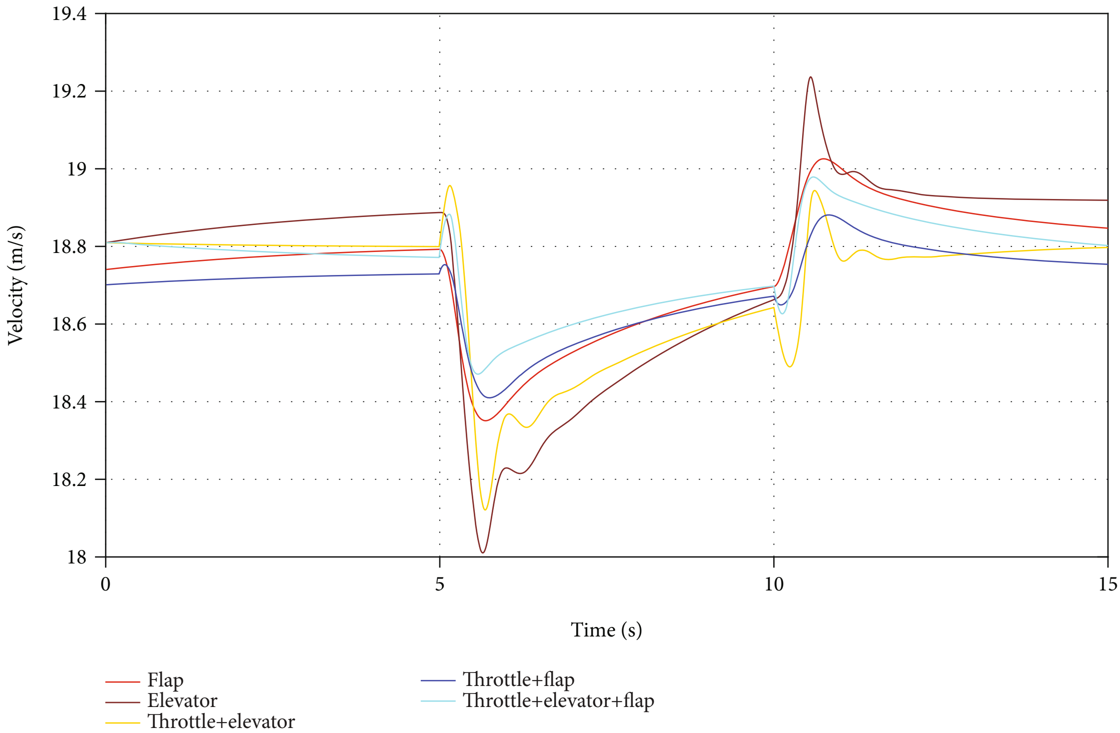


(a)



(b)

Figure 5: Continued.



(c)

FIGURE 5: Comparison of free-flight simulation results for different control systems with 1 m altitude disturbance. (a) Comparison of altitude change. (b) Comparison of pitch angle change. (c) Comparison of velocity change.

according to altitude change. The P control system controls the height of aircraft by operating elevators. In the TP control system, the output of altitude control loop is sent to attitude control loop and throttle through pitch damper K_e and throttle damper K_T, respectively. Therefore, the TP control system controls the height of aircraft by operating throttle and elevators. In the TPF control system, the output of altitude control loop is sent to attitude control loop, throttle, and flap through pitch damper K_e, throttle damper K_T, and flap damper K_F, respectively. Therefore, the TPF control system controls the height of aircraft by operating throttle, elevators, and flaps. Figures 3(b) and 3(d) depict the structures of height control systems that combine the attitude control loop and the altitude control loop in parallel, namely, the F control system and TF control system. In these control systems, attitude control loop receives pitch angle control signals θ_c from pitch angle demand and only controls pitch angle of aircraft by operating elevators according to pitch angle change. The F control system controls the height of aircraft by operating flaps. In the TF control system, the output of altitude control loop is sent to throttle and flap through throttle damper K_T and flap damper K_F, respectively. In this way, the TF control system controls the height of aircraft by operating throttle and flaps.

As shown in Figure 4, the longitudinal equations of motion of Aero-WIG in wind axes can be written as

$$m\dot{V} = T \cos(\alpha) - D - mg \sin(\gamma), \tag{1}$$

$$mV\left(\dot{\theta} - \dot{\alpha}\right) = L + T \sin(\alpha) - mg \cos(\gamma), \tag{2}$$

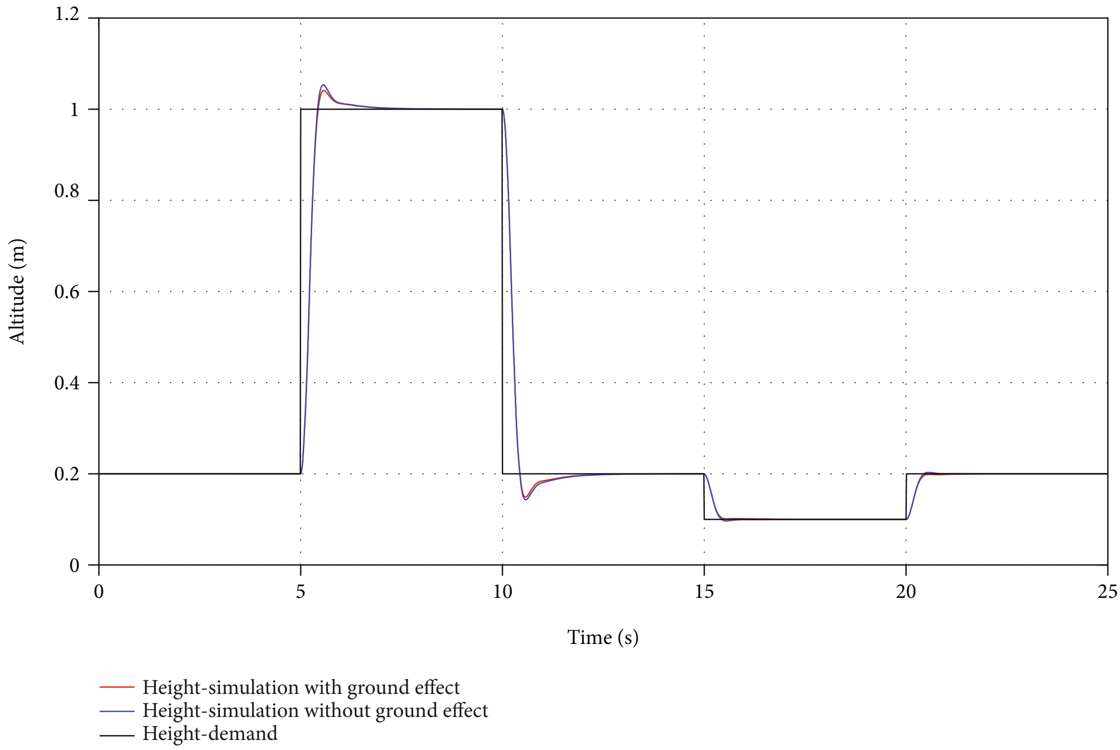
$$I_{yy}\ddot{\theta} = M, \tag{3}$$

$$\dot{\theta} = q, \tag{4}$$

$$\dot{h} = V \sin(\gamma), \tag{5}$$

where $\gamma = \theta - \alpha$ is the flight path angle. In Equation (2), $D = 0.5\rho V^2 S C_d$ is the drag. T is the thrust that can be obtained according to velocity and motor speed by using data of a 7-inch APC propeller. In Equation (2), $L = 0.5\rho V^2 S C_l$ is the lift. In Equation (3), $M_p = 0.5\rho V^2 S C C_m$, where S is the reference wing area and C is the chord length of Aero-WIG.

After the output of the control system is sent to actuators (flaps, elevators, and throttle), the aerodynamic parameters and thrust are determined according to the aerodynamic and thrust model. According to simulation results in OpenVSP, a one-degree change in flap angle translates to a 0.01 change in lift coefficient. Aerodynamic data can be obtained from the work of Su et al. [21]. Then, those parameters are put into Equation (1) to get the rate of change over time of five fundamental quantities $(V, \alpha, q, \theta, h)$. With the assumption that the rate of change remains unchanged during the time step, the state of Aero-WIG at the next time point can be obtained. With time iterating, the whole motion trail of Aero-WIG will be calculated.



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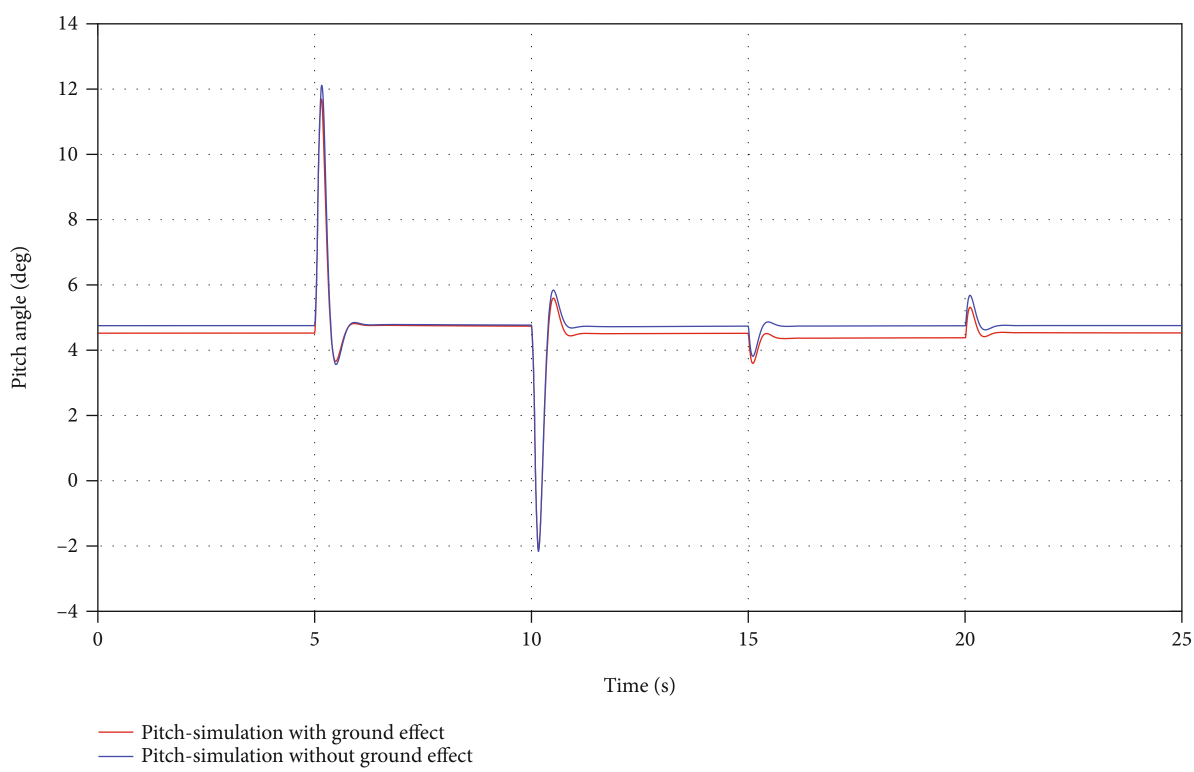
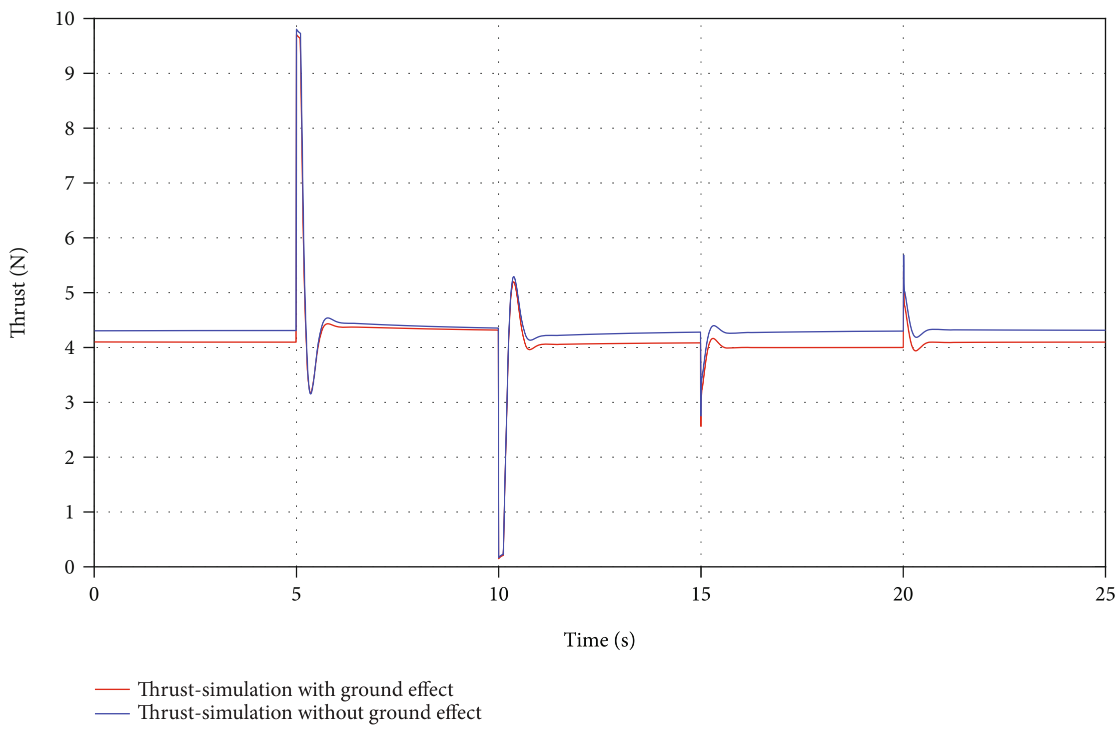


(b)

Figure 6: Continued.



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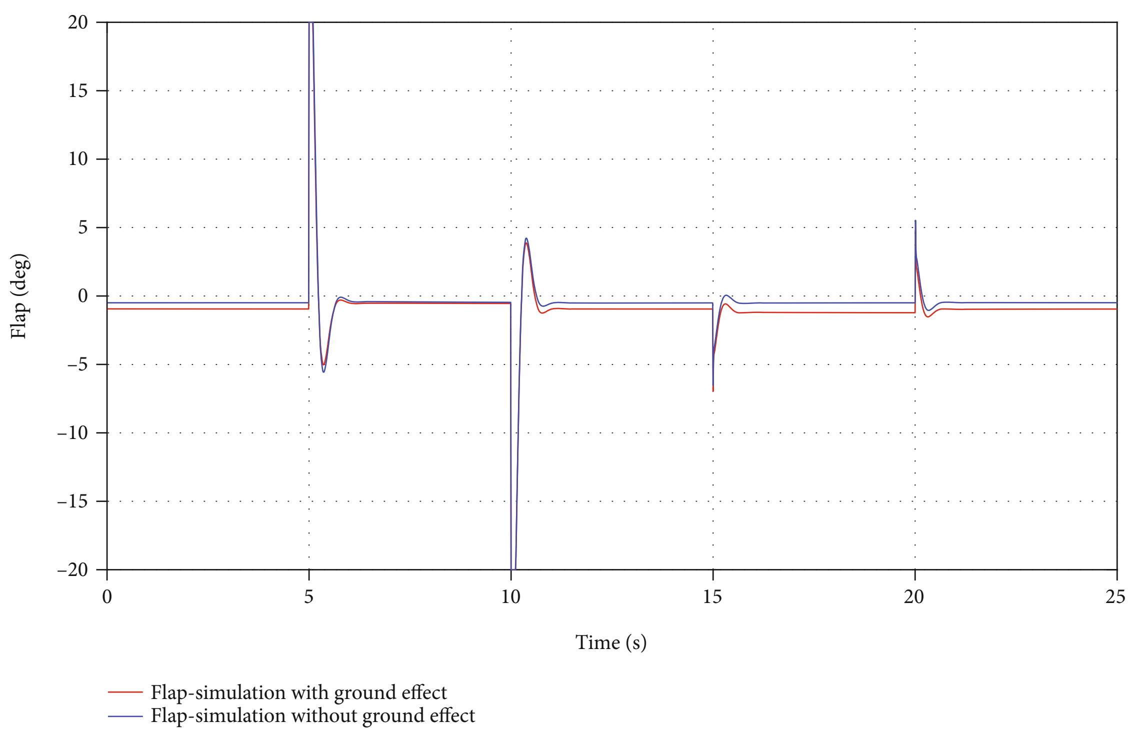
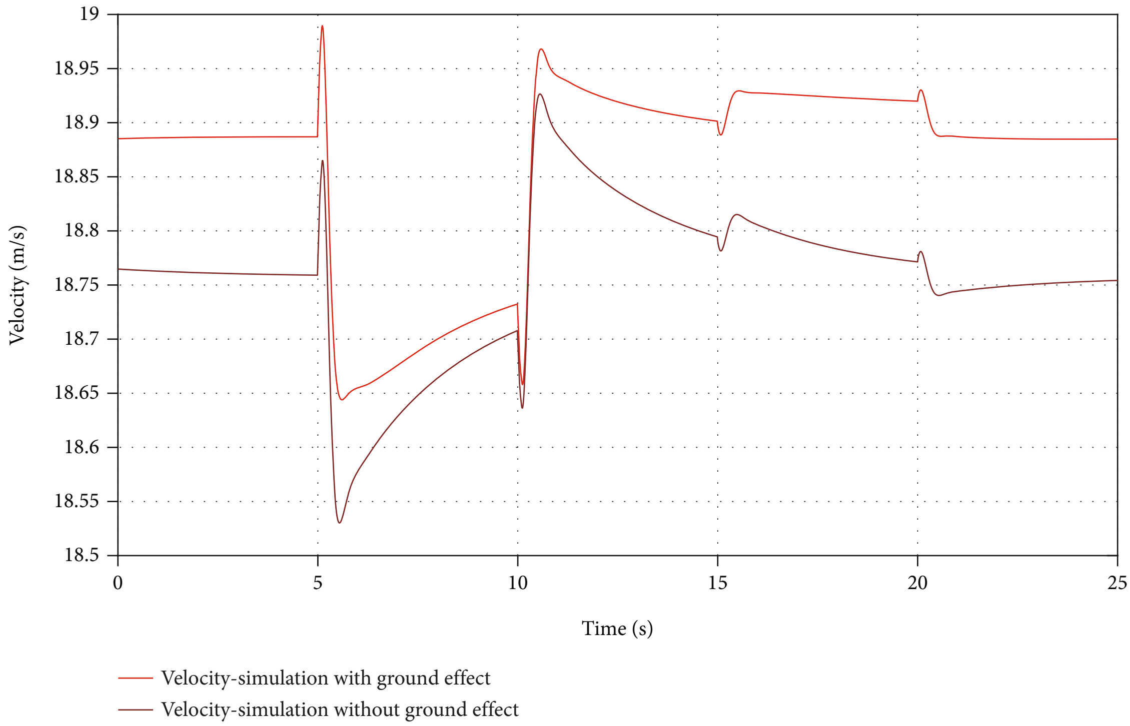


(d)

Figure 6: Continued.



(e)

Figure 6: Comparison of simulation results with and without ground effect. (a) Comparison of altitude change. (b) Comparison of oscillations in pitch angle. (c) Comparison of thrust. (d) Comparison of degrees of flaps. (e) Comparison of velocity.

3. Results and Discussion

3.1. The Comparison of the Dynamic Responses for Different Control Systems. To evaluate the performance of different control systems, the aircraft is set to cruise in a fluctuation of one meter up and down, with no ground effect influence. Results of the rising time t_r, settling time t_S, overshoot, and undershoot in the 1 m disturbed altitude simulation are illustrated in Tables 2 and 3, respectively. Comparisons of altitude change, oscillations in pitch angle, and cruise speed of different control systems in the 1 m disturbed altitude simulation are shown in Figure 5.

Since WIG crafts have to fly close to the ground, the undershoot of the control systems is much more important than overshoot. According to Tables 2 and 3, the TPF control system has the smallest undershoot, overshoot, and the shortest settling time during altitude disturbance. Nevertheless, the pitch angle of the aircraft can not be controlled independently because the controller alters the angle of elevators to control the altitude. By contrast, the TF control system and F control system can hold the pitch angle of the aircraft independently because it runs the altitude control and attitude control loops in parallel, which means elevators are only used for attitude control. Therefore, the F and TF control systems can reduce the oscillation of pitch angle of the aircraft during the altitude change. In addition, as shown in Figure 5(c), operating throttle helps reduce the velocity change during the altitude change.

3.2. The Performance of the TPF Control System in Ground Effect. To evaluate the influence of ground effect on the Aero-WIG's flight, a simulation was run that the TPF control system is utilized to hold the altitude of the aircraft under the influence of ground effect. Results are compared with those without the effect of ground effect and shown in Figure 6. As illustrated in Figure 6(a), the changes in altitude are fairly similar, which means the TPF control system is also appropriate for the Aero-WIG under the influence of the ground effect. In addition, as shown in Figures 6(b)–6(d), the thrust, pitch angle, and degrees of flaps of the aircraft with ground effect are all smaller than those of the aircraft without ground effect. Since the smaller degrees of flaps are, the smaller lift coefficient C_l of the aircraft is, it can be deduced that at the same altitude, the lift force the aircraft needs is smaller with the help of ground effect so that the aircraft can fly efficiently: cruise faster with smaller throttle at the same time.

4. Conclusions

In this paper, five different control systems for small unmanned WIG crafts are compared in simulations without ground effect. Then, simulations are done using the TPF control system with ground effect to study the influence of ground effect. The TPF control system's settling time and overshoot are the shortest and the smallest, with fluctuations in pitch angle during altitude disturbance. While the TF control system behaves inferior to the TPF control system in terms of settling time and overshoot, it has a smaller oscillation in pitch angle. Under the influence of ground effect, the TPF control system can still assure safety and high precision height control for small unmanned WIG vehicles. To conclude, this control strategy based on the PID controller can realize high precision height control for small unmanned WIG crafts and has promising practical application in WIG craft development.

In the future, experiments will be conducted to prove the effectiveness of the precise height control systems proposed in this paper. Additionally, experiments that the Aero-WIG flies at different altitudes will also be conducted to verify the simulation results in this paper.

Nomenclature

C_l: Lift coefficient
C_d: Drag coefficient
C_m: Pitching moment coefficient
C: Chord length
g: Acceleration due to gravity
m: Mass of Aero-WIG
q: Pitch rate, angular velocity about the y-axis
u, v, w: Velocity along the x, y, z axes in terrestrial coordinate systems
L: Lift
D: Drag
M_P: Pitch moment
T: Thrust
V: Velocity
α: Angle of attack
θ: Pitch angle
γ: Climbing angle
δ: Elevator
δ_e: Elevon deflection angle
ρ: Density
S: Reference wing area
h: Height of Aero-WIG
h_c: Reference height input
e_h: Error of height
θ_c: Reference pitch angle input
e_θ: Error of pitch angle
P_h: Proportional gain of height
e_h: Error of height
P_w: Proportional gain of velocity in z axes
I_w: Integral gain of velocity in z axes
D_w: Derivative gain of velocity in z axes
P_θ: Proportional gain of pitch angle
P_q: Proportional gain of pitch angle rate
I_q: Integral gain of pitch angle rate.

Data Availability

7-inch APC propeller performance data can be downloaded by visiting https://www.apcprop.com/technical-information/file-downloads/.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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