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PID Control and Simulation Analysis of DC Motor for UAV Application

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Abstract:

In contemporary society, the rapid advancement of technology has facilitated the widespread adoption of proportional-integral-derivative (PID) control systems, which are among the most employed closed-loop systems across various applications. PID control is widely used in the field of automatic control, enabling precise management of dynamic systems. However, within the specific context of unmanned aerial vehicles (UAV), proportional-integral (PI) control currently prevails due to its effectiveness under certain flight conditions. This study aims to design a PID control system specifically tailored for UAV applications. To achieve this objective, the research compares the performance of PID control with that of PI, proportional-derivative (PD) control, and Proportional (P) control. This comparative analysis will facilitate a thorough evaluation of the advantages and efficacy of the PID approach in enhancing UAV performance. After the contrast, the study finds a specific combination of the PID control to make the UAV performance more stable and effective. The study enhances the UAV's performance in future applications.

Keywords: PID control; Simulation analysis; UAV

1. Introduction

The history of intelligent UAV research is closely related to the rapid development of microelectromechanical systems. In recent years, with the vigorous development of microelectromechanical systems and the application of microprocessors with high computing speed and low power consumption, the development and research of intelligent UAVs have made major breakthroughs [1]. Intelligent UAVs are relatively common, simple, and easy-to-control multi-rotor aircraft. They possess the capability for both horizontal and vertical lifting, allowing them to change flight direction based on their orientation. These UAVs can perform various tasks such as detection, aerial photography, agricultural activities, and transportation in hazardous environments according to operator requirements. Additionally, they offer a solution to urban traffic congestion and have advantages in traversing challenging terrains like mountains and lakes [2, 3]. Therefore, to realize a better control performance, the study is going to use PID control. The effectiveness of PID controllers for a large class of process systems has ensured their continued and widespread use in industry [4]. PID control is certainly the most widely used control strategy today. It is estimated that over 90% of control loops employ PID control, quite often with the derivative

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gain set to zero (PI control) [5]. However, when using a PI control system to manage the UAV's motor speed and achieve a preset height, there are some delays in the process. The UAV takes a certain amount of time to reach the preset motor speed and subsequently stabilizes at a specific speed to maintain a hover at the intended height. Based on simulation tests, the response time of the UAV is approximately one second. During this period, before the motor speed reaches a steady state, the system may experience an overshoot. This behavior reflects a common challenge in practical application, the UAV floating above and below the targeted height. Given these limitations, this study aims to implement a PID control system to address these issues effectively. The primary challenges identified include designing a control system for the speed of the DC motor and tuning the values of the three components of the PID controller. To overcome these challenges, the study employs various simulation tools to replicate the dynamics of the DC motor control system. Additionally, a debugging method is utilized to fine-tune the coefficients of the proportional, integral, and derivative components, thereby enhancing system stability and preventing saturation of the operational amplifier.

Ultimately, the main objective of this research is to achieve a more stable control system with a faster response time. This improvement is anticipated to significantly enhance the overall performance of the UAV, allowing it to maintain its altitude more effectively and respond swiftly to any changes in control inputs.

2. Methodology

2.1 Basic principles of PID controller

This study aims to realize controlling the UAV to hover at a specific height smoothly and respond quickly.

PID controller is one of the most commonly used feedback controllers, which is composed of three parts: P, I and D. PID controllers can adjust the output of the system to provide good control performance in a variety of dynamic systems. In practical applications, when high-order information is either unavailable or challenging to acquire, PID control and second-order controllers continue to be the predominant methods employed [6].

In short, the functions of each PID controller correction link are as follows:

(1) Proportional part: proportional to reflect the control deviation error, once the deviation occurs, the controller immediately controls the system to reduce deviations.

(2) Integration part: mainly used to eliminate steady-state error. The strength of the integration effect depends on the integration time. But it will raise some oscillations.

(3) Derivative part: reflects the change trend (change rate) of the step response, and can be used to eliminate the oscillation [7].

As for the UAV, its speed curve will be complex and linear when controlling it rises to a certain height and hovers. As a result, the study chooses a PID controller to realize controlling UAVs.

So, what's the basic theory of PID control. As the study said before, a PID controller is a complex linear controller. It uses an integrator and differentiator to realize complex linear control, as shown in Fig. 1.

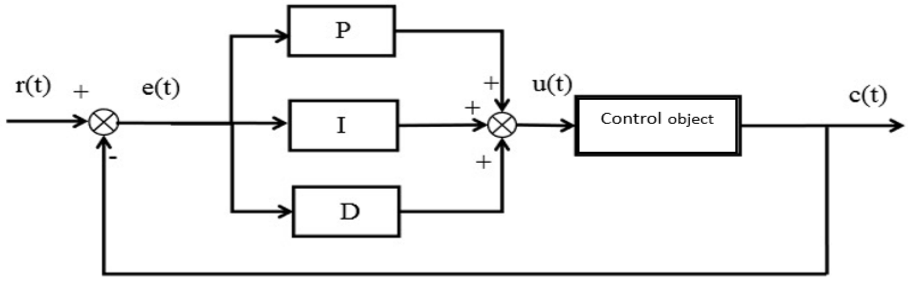

Fig. 1 Schematic Diagram of PID control. (Photo/Picture credit: Original)

Its normal theory is

$$V(t) = k_P e(t) + k_I \int_0^t e(t)\,dt + k_D \frac{de(t)}{dt} \qquad (1)$$

The number value of the proportional coefficient (k_P), integrator coefficient (k_I), and differential coefficient (k_D) can be changed to achieve a better control effect.

2.2 Tools for Simulation

2.2.1 Falstad

Falstad is an online simulation tool. It can stimulate and design a circuit model. Also, it can reflect the voltage and current throughout the circuits. Moreover, it can show us the step response of the circuits. The study will use it to design and simulate the control circuit model of the UAV.

2.2.2 Tinkercad

Thinkercad is an online simulation tool. It can stimulate and design a circuit. It can stimulate and reflect the step response on an oscilloscope just like a real circuit. The study will use it to design and simulate real circuits.

2.2.3 Octave

Octave is an online website that can be used to analyze data and process images. It is functionally similar to MATLAB but it is free and convenient to use. The study will use it to analyze the data and process the image of the circuit's root locus, pole, and zero.

3. Results and Discussion

3.1 UAV Control System Design

3.1.1 UAV control system

For the initial design of the control system of the UAV, controlling the speed of the DC motor is paramount when the UAV is asked to achieve a specific altitude. So, this study employs a DC motor model that turns voltage input to motor speed. As illustrated in Fig. 2, the study uses operational amplifier principles to develop a UAV control system. The entire system comprises five components: inverting summing; inverting gain; PID controller model; DC motor model for converting voltage to motor speed; and inverting speed output. Fig. 2 presents the circuit diagram of the control system. Regarding the PID controller segment, this study integrates its three components— P, I, and D—to streamline and enhance user convenience within the system.

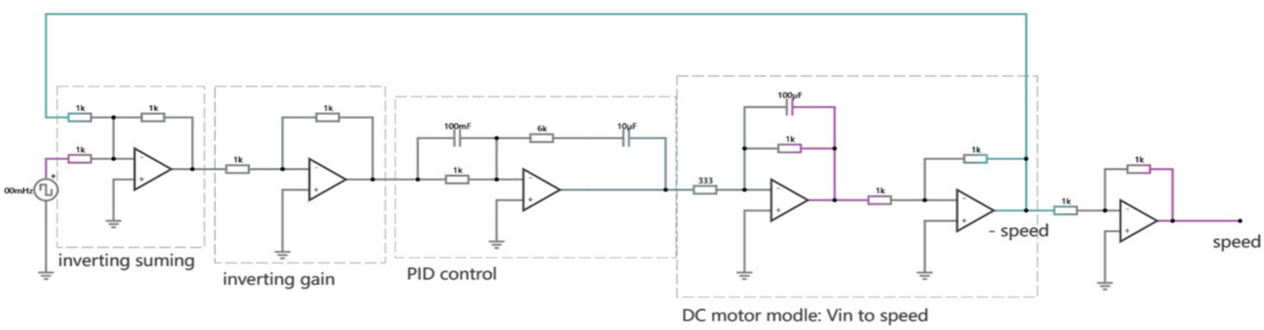

Fig. 2 Falstad simulation design. (Photo/Picture credit: Original)

For the actual simulation, this study utilizes Tinkercad. The Tinkercad model comprises five components just like Fig. 3. However, it also has some differences: an oscilloscope has been added to display the step response and the Tinkercad uses the sources as the ground. The simulation within Tinkercad is based on the circuit model designed in Falstad.

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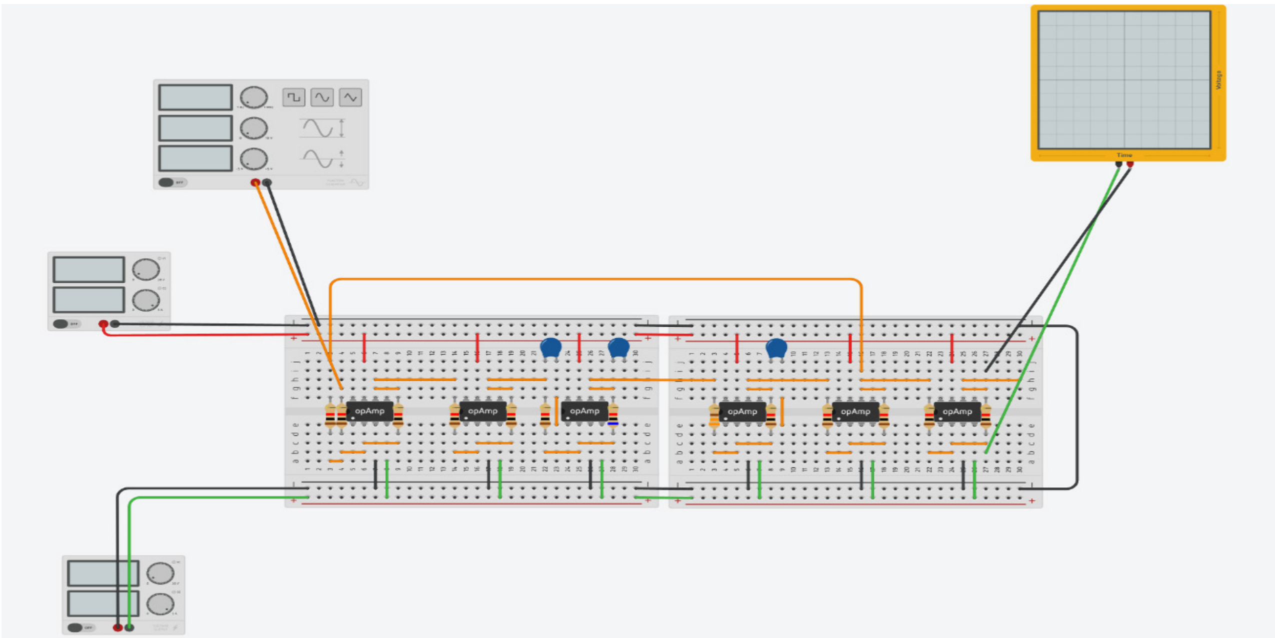

Fig. 3 Tinkercad simulation design. (Photo/Picture credit: Original)

All the above are the simulations of the circuits model. The details are shown in Figs. 2 and 3.

3.1.2 Parameter Determination and Correction of PID Controller

There has been continued interest from academia in devising new ways of approaching the PID tuning problem [8]. The study is going to use a debugging method to adjust the parameter of the coefficient of three parts.

Before adjusting the parameter, it is a must to know how to define the coefficient of three parts. In Fig. 4, the study has figured out the relationship between the three coefficient and the resistor and capacitance:

$$k_p = \frac{R_2}{R_1} + \frac{C_1}{C_2} \tag{2}$$

$$k_I = \frac{1}{R_1 * C_2} \tag{3}$$

$$k_D = R_2 * C_1 \tag{4}$$

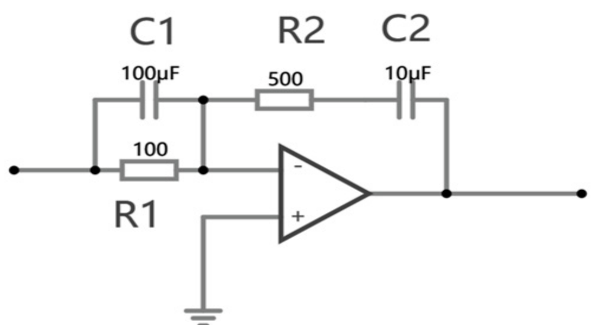

Fig. 4 Circuit of a PID controller. (Photo/Picture credit: Original)

After several attempts and considering the convenience of the setting. Finally, the study chooses to set kp = 15, ki = 1, kd = 5. Because in this form of the PID controller, the coefficients are influenced by each other. It is really difficult to define so the study needs to set a combination that is easy to calculate and to set in the circuit, also, avoid saturating. For the details, the study set C1 = 100uF, C2 = 10uF, R1 = 100ohm, R2 = 500ohm as Fig. 5 showed. Also, for the features of the motor, the study sets its transfer function equal to $\frac{3s}{0.1s+1}$ Fig. 5 shows the number value of each electronic component model which is in line with the transfer function.

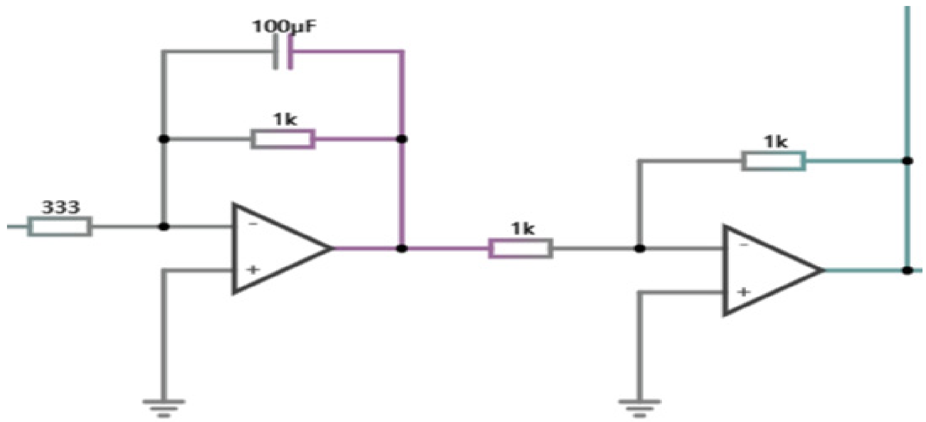

Fig. 5 DC motor model: Vin to-speed. (Photo/Picture credit: Original)

3.2 Simulation Analysis of the Control Effect Based on the PID Controller

3.2.1 Control Function Simulation Results

After confirming the parameter of the three coefficients, the study sets the combination of the two simulation tools. The following are the results of the simulation. Figs. 6 and 7 correspond to each other. It is seen that it can get to the stage very quickly in 0.05 seconds and it only has a 0.05 voltage overshoot. The results are satisfactory for the response time and the oscillation. So, the next part of the study wants to have a look at the influence of each part.

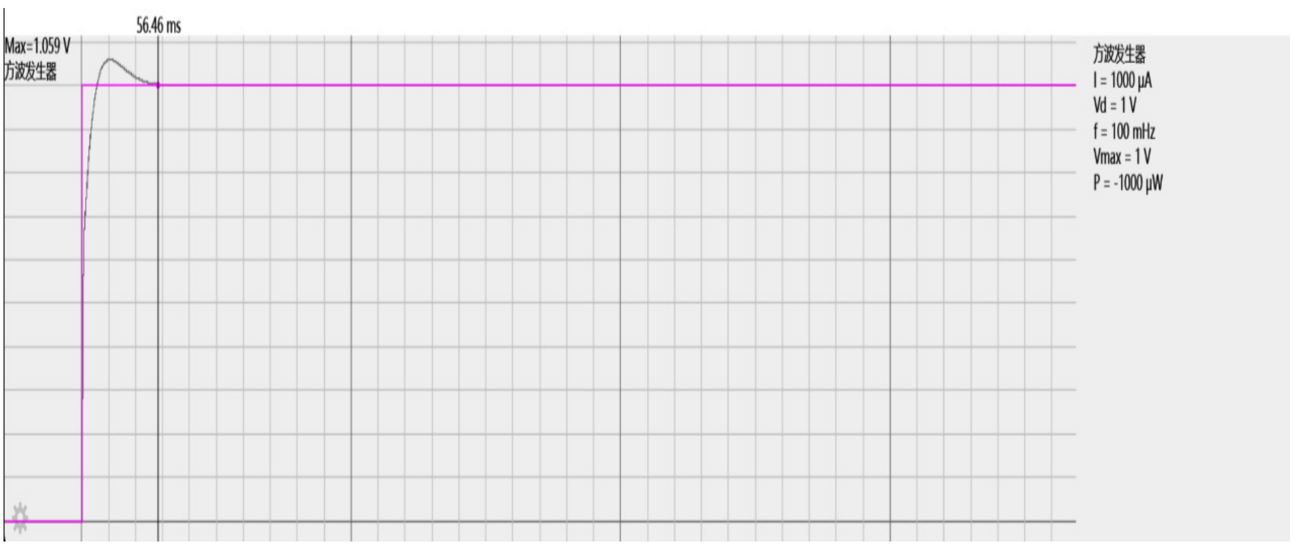

Fig. 6 Falstad simulation result. (Photo/Picture credit: Original)

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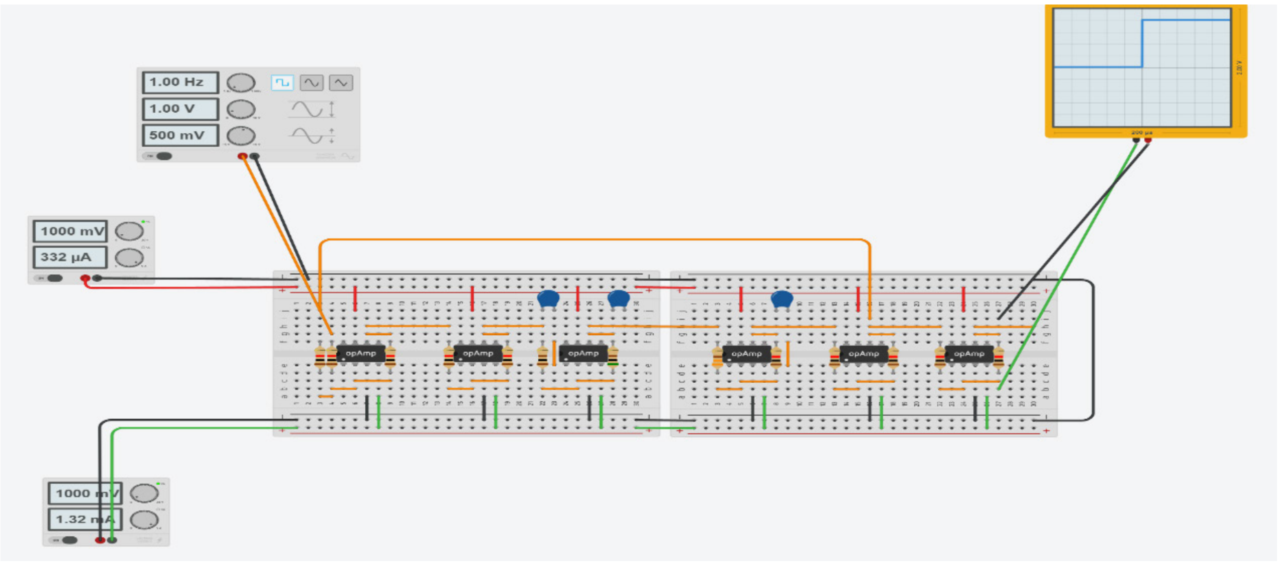

Fig. 7 Tinkercad simulation result. (Photo/Picture credit: Original)

Before the study starts analyzing the effect of the three controllers, it is necessary to have some knowledge of the three controllers. Fig. 8 shows the circuit model of the three controllers. The study will change the controller parts to analyze the influence of these three controllers.

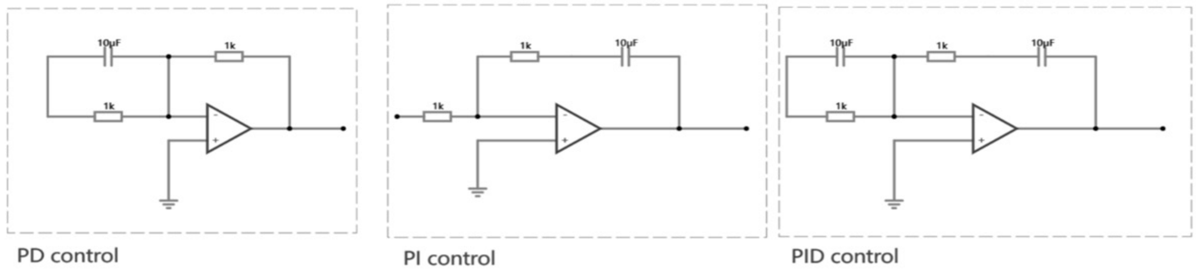

Fig. 8 Circuits model of three controllers. (Photo/Picture credit: Original)

3.2.2 Control Effect of the PI Controller on remove steady error

So, the study is going to make a comparison between the P control and the PI control to have a look at the main function of the integrator part. In Figs. 8 and 9, the upside (Fig. 9) is P control, it can't reach the highest voltage that the study wants. That is called steady error. With only P control, the steady error will occur so the system can't control the UAV to the specific flight height. So, the study needs to add Integrator control to remove the steady error, and the result is as Fig. 10. The result is that the steady error is removed. But there are some new problems: first and foremost, before the system gets to the stage, there are some oscillations occur. This makes the system appear unstable. Besides, the time for the system to get to the stage is longer than the former. This makes the response time longer.

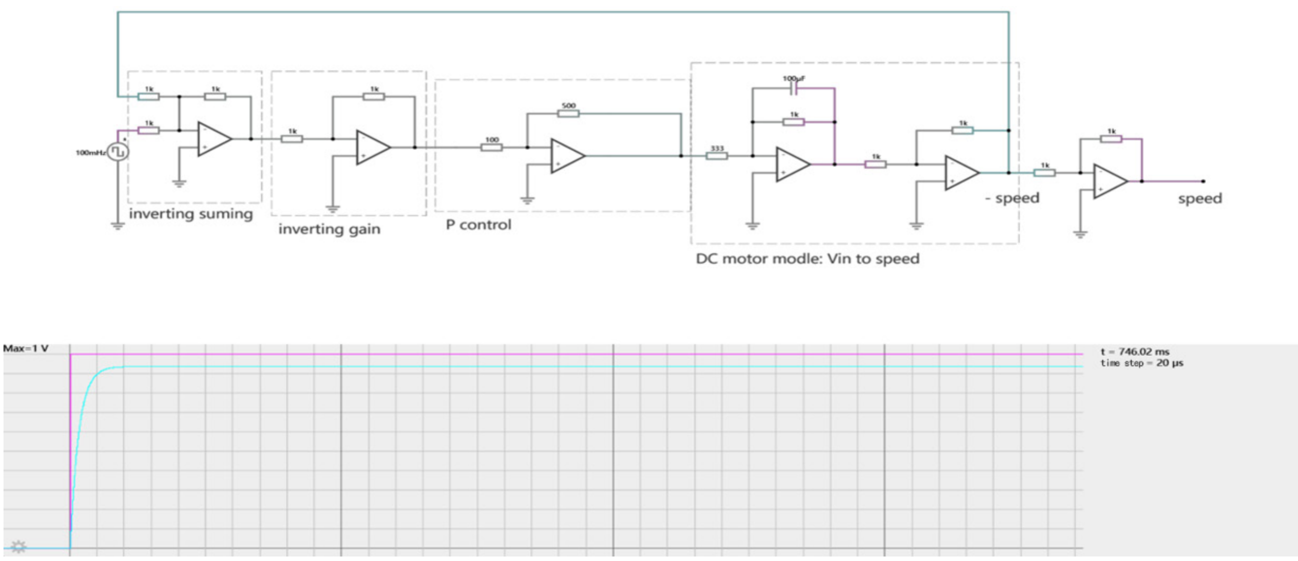

Fig. 9 Effect based on P control. (Photo/Picture credit: Original)

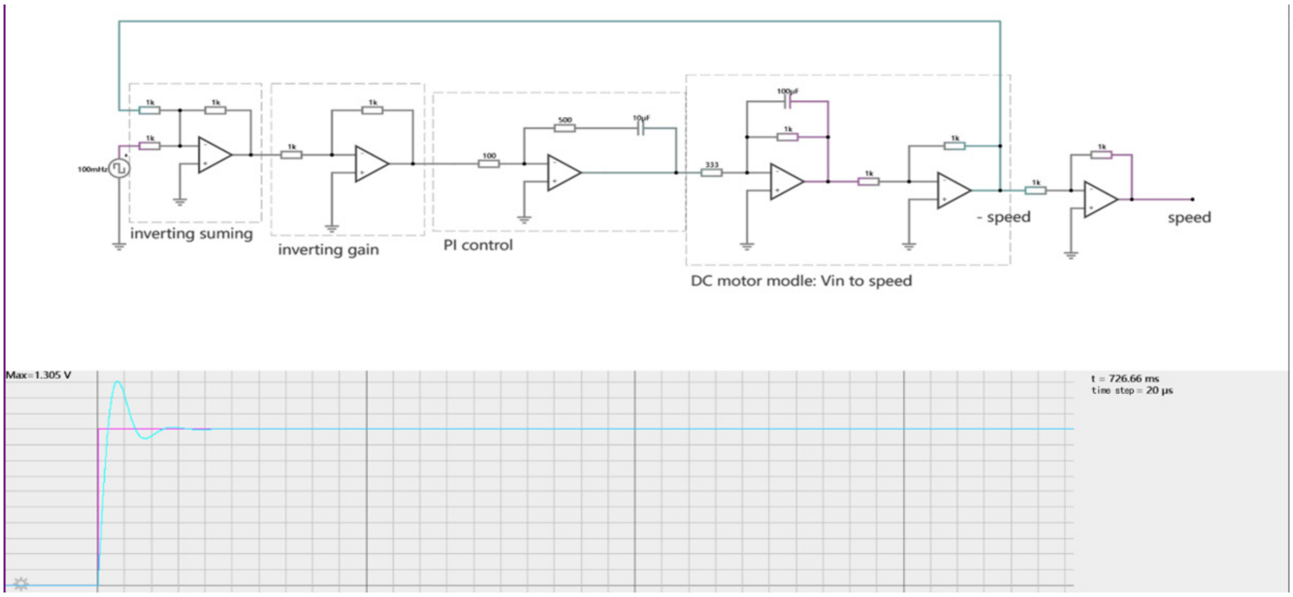

Fig. 10 Effect based on PI control. (Photo/Picture credit: Original)

3.2.3 Control Effect of the PD Controller on response time and oscillation

So, the study is going to take derivative control to solve the new problems. For the effect of the PD controller, please have a look at Fig. 11. Then make a comparison with Fig. 9. The oscillation is removed. Moreover, the time to get to the stage is greatly reduced. But there are still some steady errors. Only using the PD controller can make the system respond quickly and more stable. But it still can't reach the specific height when controlling it because of the existence of steady error.

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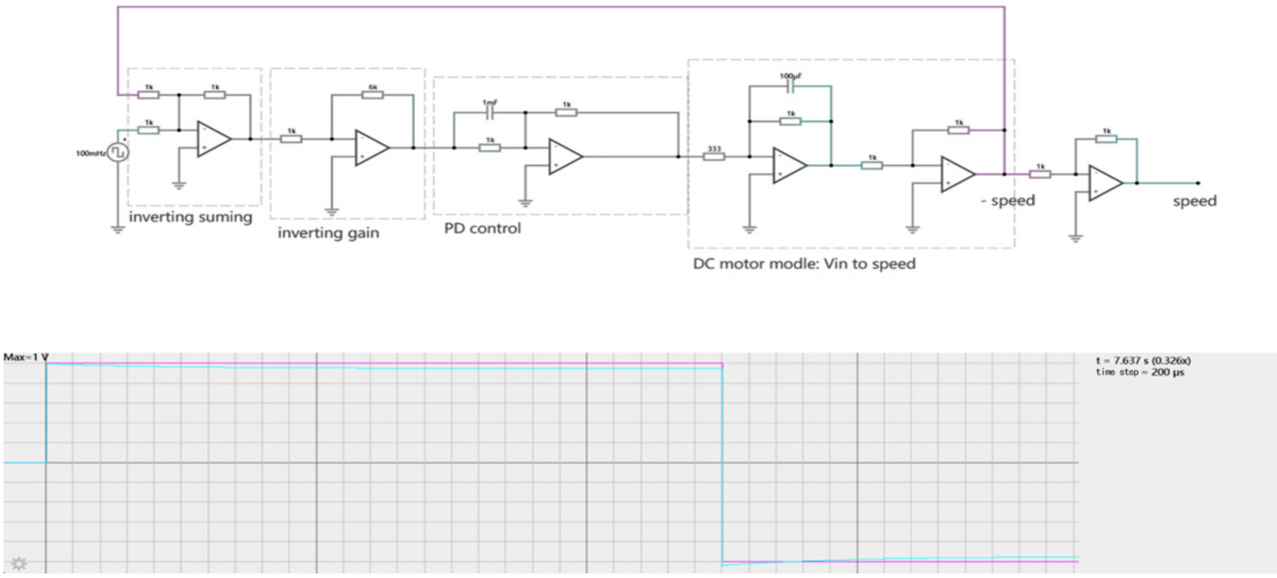

Fig. 11 Effect based on PD control. (Photo/Picture credit: Original)

3.2.4 Control Effect of the PID Controller for UAV application

As the study said before, it sets kp=15, ki=1, kd=5. Since it is a PID controller, the C(s) should be

$$C(s) = k_P + \frac{k_I}{s} + k_D * s \quad (5)$$

Take the data into the formula. Then using octave calculate the C(s) times the transfer function of the DC motor which turns the voltage to speed.

So, the study decided to combine these three parts to realize the control. By combining the advantages of the three, the study can get optimized control performance [9]. With its three-term functionality offering treatment of both transient and steady-state responses, proportional-integral-derivative (PID) control provides a generic and efficient solution to real-world control problems [10]. Then, after many attempts of the parameter, the study gets a satisfactory result as shown in Fig. 6. It demands all the requirements that the study asked. The study also used octave to examine the result again. The octave is used to examine the stability of the control system. Finally, use the octave to draw the diagram of the root locus and zero and open loop poles of the function (Fig. 12). It can be found that the locus is all to the left of the imaginary axis. It means that the control system is stable.

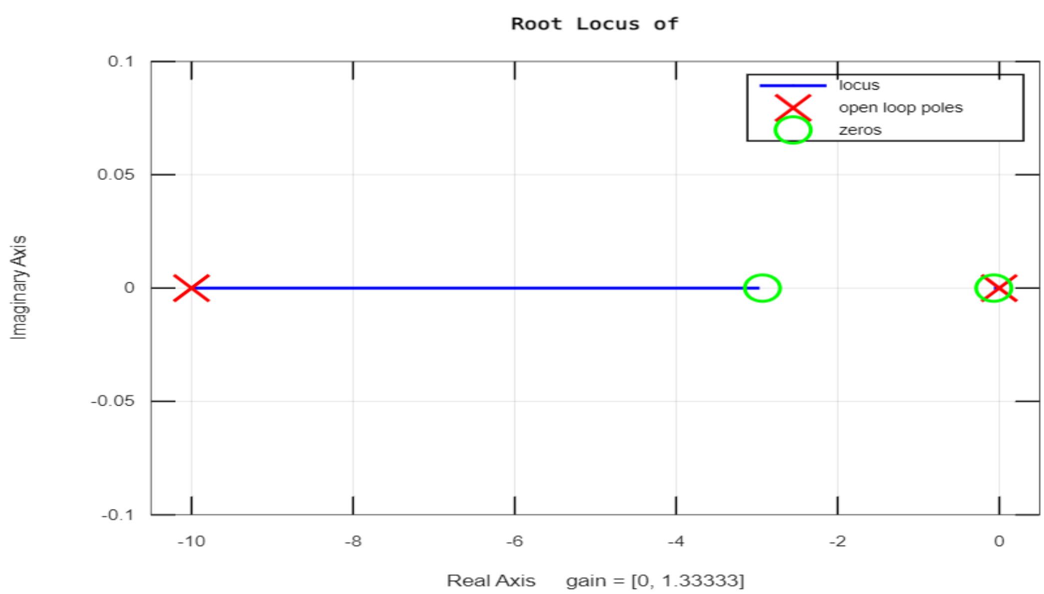

Fig. 12 Octave simulation (kp=15, ki=1, kd=5). (Photo/Picture credit: Original)

4. Conclusion

After a thorough comparison of the effects of PID control, PI control, PD control, and P control, this study draws several key conclusions regarding their effectiveness in UAV systems. P control enables the system to reach a specific target stage but is accompanied by steady-state error, which can hinder overall performance. In contrast, PI control effectively reduces this steady-state error, thereby improving accuracy, although it may introduce some overshoot in the process. PD control, on the other hand, is particularly effective at addressing these overshoots, enhancing the stability of the transient response, and facilitating the achievement of the desired stage.

Integrating these three control strategies into a single controller emerges as a robust solution for ensuring that UAV systems can attain preset values both smoothly and accurately. It is well established that PI controllers are widely used in UAV applications due to their effectiveness. The findings of this study indicate that when a UAV is commanded to reach a specific altitude, oscillations around that altitude are likely to occur. However, by incorporating D control into the mix, these oscillations can be minimized, resulting in smoother altitude attainment and improved responsiveness. The implications of this study for future UAV control systems are substantial. Although the discussions presented are primarily based on simulations and theoretical frameworks, there remains significant potential for further analysis of various UAV operational forms. Such exploration could enhance the practical application of PID control systems, ultimately leading to more effective and reliable UAV controlling.

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