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Analysis and design of –PID controller for a quadrotor in the frequency domain

Alhassan Dodo Adamou Soudeize*, Ji-Sun Park*, Ho-Lim Choi*★

Abstract

In this paper, we propose an ϵ-PID controller for the altitude control of the quadrotor from the ground by considering the mass of the AR Drone and external disturbance. The first part consists of modeling the quadrotor and carrying out the system analysis with the proposed controller and the second part consists of carrying out the experiment in the lab to show that our control method along with the analysis coincides with the experiment.

Key words : Quadrotor, Uncertain mass, External disturbance, Frequency analysis, Nonlinear systems

Ⅰ. Introduction

The development of unmanned aerial vehicles (UAVs) such as functional quadrotors since the beginning of the 2000s has attracted much attention and has been applied to various tasks, from military to entertainment applications [1].

Naturally, the control research field has been more attracted to this topic since quadrotors present complex and nonlinear dynamics while having four input forces which are the thrust forces provided by each propeller connected to each rotor at a fixed pitch angle. The way of controlling a quadrotor is by varying the speed of each rotor, which implies that the delivered force by each propeller also varies as described in [2]. In [2], when the rotating velocities of all four motors are increased at the same amount, the quadrotor will fly upwards. When the left and right rotors operate at different speeds, the quadrotor will tilt around its longitudinal axis and fly rightward or leftward, depending on which motor rotates faster. Similarly, the quadrotor will tilt around its transverse axis and fly forward and backward depending on the front and rear motors. The yaw rotation is caused by the difference between the angular momentum generated by these two pairs of rotors. Therefore, the roll, pitch, and yaw angles, and total thrust can be utilized as the control variables for the onboard control of the quadrotor.

In our approach to the altitude control of a quadrotor, z-the altitude of the quadrotor is achieved through the implementation of the output feedback controllers to each axis. The three axis regulation is achieved by implementing the simultaneous modified ϵ-PID controller over the axes and flight tests as performed in [3]. The

* Dept. of Electrical Engineering, Dong-A University
★ Corresponding author
E-mail : hlchoi@dau.ac.kr, Tel : +82-51-200-7734
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altitude control is achieved by using ultrasonic sensor. In altitude hold mode, quadrotor maintains the altitude while allowing roll, pitch, and yaw to be controlled normally. One of the challenging aspect in the control of a quadrotor is the disturbance due to the weight of the quadrotor or the weather climate which is proposed in [4]. There have been also various types of disturbance observer (DOB) applied to UAVs. S. H. Jeong et al. [5] proposed an acceleration based DOB for the attitude control of a quadrotor UAV. H. Wang et al. [6] proposed a linear dual DOB on attitude control with attention restricted in tracking control of quadrotor UAVs. As it can be seen, these work are all motivated by the attitude control of quadrotor UAVs. In order to achieve a better control effect, the error-state model predictive control of quadrotors proposed by [7].

In this paper, we apply an ϵ-PID controller to the altitude control of a quadrotor. We formally present a system analysis with respect to the control parameters in frequency domain in terms of the system stability and control performance. Then, based on the analysis, we set the parameters of the controller and apply to the actual quadrotor system. From the experimental results, we verify the validity of our control method.

II. System dynamics of quad-rotor

Consider the diagram below from [8] in which

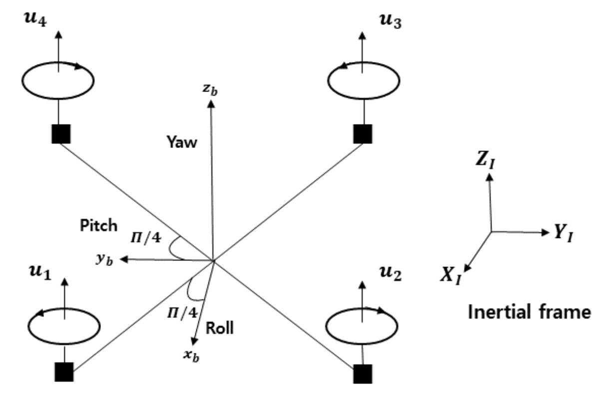


Fig. 1. Configuration of a quadrotor.

x_b, y_b, z_b represent the body fixed frame, $u_i (i = 1,2,3,4)$ denote the inputs of each motor and X_I, Y_I, Z_I denote the earth fixed frame.

We consider the dynamic equation of the quadrotor with time-varying mass and external disturbance of [9] expressed as follows

$$\ddot{z} = [(\cos\phi\cos\theta)U_z]/m - g + d_z(t) \tag{1}$$

$$\ddot{\phi} = [lU_\phi + \dot{\theta}\dot{\psi}(I_y - I_z)]/I_x + d_\phi(t) \tag{2}$$

$$\ddot{\theta} = [lU_\theta + \dot{\phi}\dot{\psi}(I_z - I_x)]/I_y + d_\theta(t) \tag{3}$$

$$\ddot{\psi} = [U_\psi + \dot{\phi}\dot{\theta}(I_x - I_y)]/I_z + d_\psi(t) \tag{4}$$

From Fig. 1, z is the altitude of the quadrotor from the ground, ϕ, θ, ψ are roll, pitch and yaw angles respectively. The acceleration due to gravity is given as g and I_x, I_y, I_z are moments of inertia about the x, y and z axis, l is the distance between the motors and the center of the quadrotor. The total mass of the quadrotor is given as \$m\$ which is expressed as $m = m_0 + \delta_m$ where m_0 is the nominal mass and δ_m is the uncertain mass. On the other hand, $d_i(t)$ $(i = z, \phi, \theta, \psi)$ are the uncertain external disturbances. The control inputs of the quadrotor $U_i (i = z, \phi, \theta, \psi)$ are given as follows

$$U_z = K_t(u_1 + u_2 + u_3 + u_4) \tag{5}$$

$$U_\phi = K_t(-u_1 + u_2 + u_3 - u_4) \tag{6}$$

$$U_\theta = K_t(u_1 + u_2 - u_3 - u_4) \tag{7}$$

$$U_\psi = K_t(-u_1 + u_2 - u_3 + u_4) \tag{8}$$

The following assumptions have been considered.

1. The uncertain external disturbances, $d_i(t)$ $(i = z, \phi, \theta, \psi)$ are bounded as $|d_i(t)| \le \overline{d_i}$ where $0 < d_i \le 1$.
2. The δ_m is less than 10% of m_0, i.e., $0 \le \delta_m \le 0.1 m_0$.
3. The Euler angles are bounded as $|\phi| \ll \pi/2$, $|\theta| \ll \pi/2$, $|\psi| \ll \pi$ as a result, $\cos\phi = \cos\theta \approx 1$ and $\sin\theta \approx \theta$ since the quadrotor operates with

small angles (ϕ,θ).

Under Assumptions $1 \sim 3$ after the Jacobian Linearization, equations (1) to (4) become

$$\ddot{z} = U_z/(m_0+\delta_m) - g + d_z(t) \tag{9}$$

$$\ddot{\phi} = [l U_\phi]/I_x + d_\phi(t) \tag{10}$$

$$\ddot{\theta} = [l U_\theta]/I_y + d_\theta(t) \tag{11}$$

$$\ddot{\psi} = U_\psi/I_z + d_\psi(t) \tag{12}$$

Let $U_z = m_0 C_z + m_0 g$ Equation (9) becomes

$$\begin{aligned}\ddot{z} &= \frac{m_0 C_z + m_0 g}{m_0+\delta_m} - g + d_z(t)\\ &= \frac{m_0 C_z}{m_0+\delta_m} + \frac{\delta_m}{m_0+\delta_m} g + d_z(t)\end{aligned} \tag{13}$$

Taking the Laplace transform of equation (13) with zero initial condition we get.

$$\ddot{z} = \frac{m_0}{m_0+\delta_m} C_z(s) + \frac{\delta_m}{m_0+\delta_m}\frac{g}{s} + D_z(s) \tag{14}$$

Expressing the system of equation (14) in a block diagram along with a feedback PID controller, we have

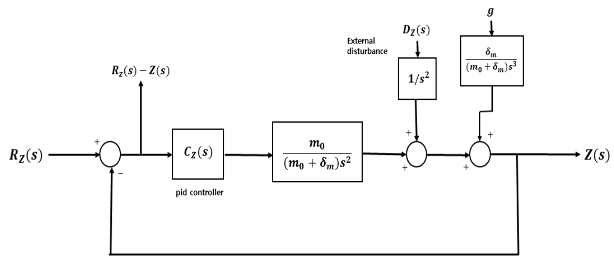


Fig. 2. Control scheme for the altitude of the quadrotor (z parameter).

Then the corresponding transfer function for Fig. 2 is expressed as

$$\begin{aligned}Z(s) &= \frac{m_0 C_z(s)}{m_0 C_z(s) + s^2(m_0+\delta_m)} R_z(s)\\ &+ \frac{m_0+\delta_m}{m_0 C_z(s) + s^2(m_0+\delta_m)} D_z(s)\\ &+ \frac{g\delta_m}{C_z(s) m_0 s + s^3(m_0+\delta_m)}\end{aligned} \tag{15}$$

Ⅲ. Controller design and system analysis

1. ϵ−PID controller

In this section, we propose a PID controller with a gain-scaling factor ϵ for a quadrotor with an uncertain mass and external disturbances. We aim to reduce the size of sates bounds by varying the gain-scaling factor from $0 < \epsilon \le 1$. Our Proposed controller is as follows

$$C_z(s) = k_P(\epsilon) + k_I(\epsilon)/s + k_D(\epsilon)s \tag{16}$$

Substituting (16) into (15) gives

$$\begin{aligned}Z(s) &= \frac{(k_D(\epsilon)s^2 + k_P(\epsilon)s + k_I(\epsilon))m_0}{(m_0+\delta_m)s^3 + (k_D(\epsilon)s^2 + k_P(\epsilon)s + k_I(\epsilon))m_0} R_z(s)\\ &+ \frac{(m_0+\delta_m)s}{(m_0+\delta_m)s^3 + (k_D(\epsilon)s^2 + k_P(\epsilon)s + k_I(\epsilon))m_0} D_z(s)\\ &+ \frac{g\delta_m s}{(m_0+\delta_m)s^4 + (k_D(\epsilon)s^3 + k_P(\epsilon)s^2 + k_I(\epsilon)s)m_0}\end{aligned} \tag{17}$$

We let our proposed ϵ−PID parameters to be

$$k_P(\epsilon) = \frac{k_P}{m_0\epsilon},\quad k_I(\epsilon) = \frac{k_I}{m_0\epsilon^2},\quad k_D = \frac{k_D}{m_0\epsilon^3} \tag{18}$$

Now in order to check the system's stability and performance of our proposed ϵ−PID controller, we insert the above ϵ−PID parameters in (18) into (17) and carry out the Routh array method to proceed to the robust stability analysis.

$$\begin{aligned}Z(s) &= \frac{\frac{k_D}{\epsilon^3}s^2 + \frac{k_P}{\epsilon}s + \frac{k_I}{\epsilon^2}}{(m_0+\delta_m)s^3 + \frac{k_D}{\epsilon^3}s^2 + \frac{k_P}{\epsilon}s + \frac{k_I}{\epsilon^2}} R_z(s)\\ &+ \frac{(m_0+\delta_m)s}{(m_0+\delta_m)s^3 + \frac{k_D}{\epsilon^3}s^2 + \frac{k_P}{\epsilon}s + \frac{k_I}{\epsilon^2}} D_z(s)\\ &+ \frac{g\delta_m s}{(m_0+\delta_m)s^4 + \frac{k_D}{\epsilon^3}s^3 + \frac{k_P}{\epsilon}s^2 + \frac{k_I}{\epsilon^2}s}\end{aligned} \tag{19}$$

We perform the Routh array stability for equation (19) to check the robust stability of our system as shown in the tables below

Table 1. Routh Array of (z) for the first two parts of equation (19)

s^3	1	$\frac{k_P}{(m_0+\delta_m)\epsilon}$
s^2	$\frac{k_D}{(m_0+\delta_m)\epsilon^3}$	$\frac{k_I}{(m_0+\delta_m)\epsilon^2}$
s^1	$\frac{k_D k_P/(m_0+\delta_m)^2\epsilon^4 - k_I/(m_0+\delta_m)\epsilon^2}{k_D/(m_0+\delta_m)\epsilon^3}$	0
s^0	$\frac{k_I}{(m_0+\delta_m)\epsilon^2}$	0

Table 2. Routh Array of (z) for the third part of equation (19)

s^4	1	$\frac{k_P}{(m_0+\delta_m)\epsilon}$	0
s^3	$\frac{k_D}{(m_0+\delta_m)\epsilon^3}$	$\frac{k_I}{(m_0+\delta_m)\epsilon^2}$	0
s^2	$\frac{k_P}{(m_0+\delta_m)\epsilon^4}-\frac{\epsilon k_I}{k_D}$	0	0
s^1	$\frac{k_I}{(m_0+\delta_m)\epsilon^2}$	0	0
s^0	0	0	0

The followings are observation made from the above proposed $\epsilon-$pid controller on stability and design rule.

- Select k_P, k_I, k_D such that
$$s^3+\frac{k_D}{(m_0+\delta_m)\epsilon^3}s^2+\frac{k_P}{(m_0+\delta_m)\epsilon}s+\frac{k_I}{(m_0+\delta_m)\epsilon^2}=0$$
is a Hurwitz polynomial which makes our system robustly stable against the total mass of the quadrotor $m=m_0+\delta_m$ where δ_m is said to range from 0 to 5% of the nominal mass $(m_0=0.429kg)$.
- Reducing ϵ and by making $\delta_m=0$ will reduce the steady-state error produced by disturbance δ_m and the gravitational force g, respectively.
- Similar to [10], the selection of ϵ provides a way to robustly attenuate the uncertain parameter δ_m and there exists a practical limitation of ϵ not being smaller than its saturation as seen in [11].
- From Tables. 1 and 2, the system is said to be stable since all the terms of the first column is positive.
- From table Table. 1, if ϵ gets smaller, $\frac{k_D k_P/(m_0+\delta_m)^2\epsilon^4 - k_I/(m_0+\delta_m)\epsilon^2}{k_D/(m_0+\delta_m)\epsilon^3}$ gets bigger. As a result, ϵ provides control performance improvement.

2. Frequency analysis of proposed PID controller

Here, our main aim is to check the performance of our system by carrying out the performance analysis which consists of finding the classical control performance specifications (overshoot, damping-ratio and settling-time). Consider the transfer function in (19) expressed as

$$Z_1(s)=\frac{Z_{11}(s)}{R_{11}(s)}=\frac{\frac{k_D}{\epsilon^3}s^2+\frac{k_P}{\epsilon}s+\frac{k_I}{\epsilon^2}}{(m_0+\delta_m)s^3+\frac{k_D}{\epsilon^3}s^2+\frac{k_P}{\epsilon}s+\frac{k_I}{\epsilon^2}} \quad (20)$$

The characteristic equation is

$$(m_0+\delta_m)s^3+\frac{k_D}{\epsilon^3}s^2+\frac{k_P}{\epsilon}s+\frac{k_I}{\epsilon^2}=0 \quad (21)$$

Dividing (21) by $(m_0+\delta_m)$ gives

$$s^3+\frac{k_D}{(m_0+\delta_m)\epsilon^3}s^2+\frac{k_P}{(m_0+\delta_m)\epsilon}s+\frac{k_I}{(m_0+\delta_m)\epsilon^2}=0 \quad (22)$$

We let $\epsilon=1$ in (22) and then we obtain

$$s^3+\frac{k_D}{(m_0+\delta_m)}s^2+\frac{k_P}{(m_0+\delta_m)}s+\frac{k_I}{(m_0+\delta_m)}=0 \quad (23)$$

Equation (23) gives us an allowable range of δ_m not more than 5% of the nominal mass $(m_0=0.429kg)$ once k_P, k_I, k_D are selected. When $\delta_m=0$(no uncertainty), (23) becomes

$$\begin{aligned} & s^3+\frac{k_D}{(m_0+\delta_m)}s^2+\frac{k_P}{(m_0+\delta_m)}s+\frac{k_I}{(m_0+\delta_m)} \\ & =(s+\alpha)(s^2+2\zeta w_n s+w_n^2 \\ & =s^3+(2\zeta w_n+\alpha)s^2+(2\alpha\zeta w_n+w_n^2)s+\alpha w_n^2 \end{aligned} \quad (24)$$

where $0 < \zeta \leq 1$ and $\alpha \gg \zeta w_n$.

The effect of the third pole is desired to be negligible to make the behaviour of our proposed controller to be governed by dominant poles[10]. Therefore, under $\alpha \gg \zeta w_n$ and comparing both sides of equation (24), we get

$$\frac{k_D}{0.429} = 2\zeta w_n + \alpha > 0 \tag{25}$$

$$\frac{k_P}{0.429} = 2\alpha\zeta w_n + w_n^2 > 0 \tag{26}$$

$$\frac{k_I}{0.429} = w_n^2 \alpha > 0 \tag{27}$$

Therefore we first select α, ζ and w_n in order to determine k_P, k_I, k_D based upon the observation made above. However due to the uncertainty δ_m, from (24), we set

$$\frac{k_D}{0.429 + \delta_m} = 2\zeta w_n + \alpha > 0 \tag{28}$$

$$\frac{k_I}{0.429 + \delta_m} = 2\alpha\zeta w_n + w_n^2 > 0 \tag{29}$$

$$\frac{k_I}{0.429 + \delta_m} = w_n^2 \alpha > 0 \tag{30}$$

Since $\alpha \gg \zeta w_n$,

$$\alpha = \frac{k_D}{m_0 + \delta_m} \tag{31}$$

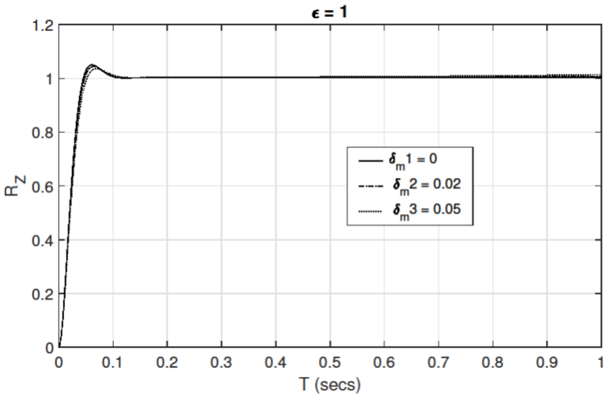
Inserting (31) into (30), we get

$$w_n = \sqrt{\frac{k_I}{(m_0 + \delta_m)\alpha}} \tag{32}$$

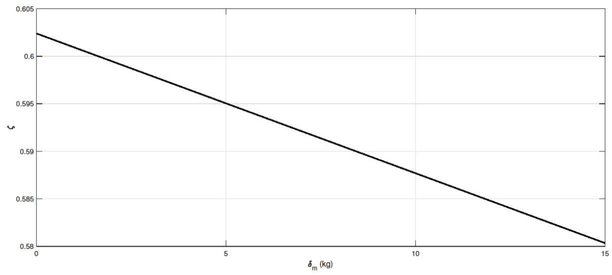
$$\zeta = \frac{k_P/(m_0 + \delta_m) - w_n^2}{2\alpha w_n} \tag{33}$$

Thus from the above equations, we observe that under $\alpha \gg \zeta w_n$, δ_m affects both ζ and w_n. We obtain the following plots and table with the following sets of k_P, k_I, k_D.

- Set 1 : $(k_P = 4, k_I = 0.5, k_D = 22)$
- Set 2 : $(k_P = 5, k_I = 3, k_D = 15)$

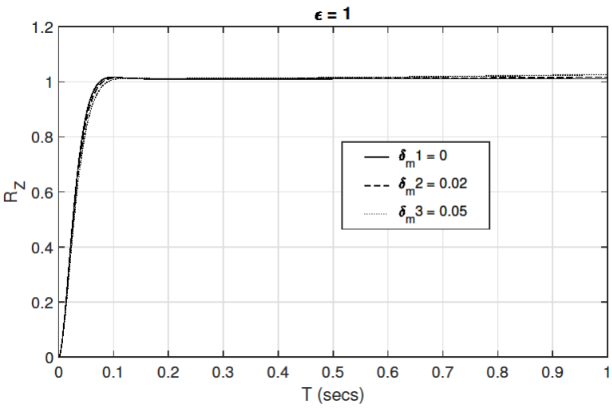


(a)

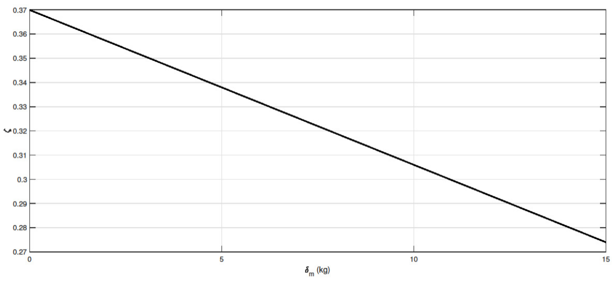


(b)

Fig. 3. (a) Step response (b) Effect of δm on ζ using Set 1.



(c)



(d)

Fig. 4. (c) Step response (d) Effect of δm on ζ using Set 2.

The following sare some observations made from the above plots in Fig. 3 and 4.

- In order to obtain the best performance of our proposed controller, the uncertainty δ_m should be no more than 10%.
- The frequency analysis are conducted to show the effect of ϵ on damping-ratio under the uncertain mass and external disturbance [10].

So from the analysis carried out in Section 3, we are able select a good set of values for k_P, k_I, k_D. This corresponds to our initial step for our proposed $\epsilon-$pid controller design.

3. Effect of on steady-state error(e_{ss})

We apply the final value theorem to the error formula with respect to ϵ. We will proceed as follows

$$e_{ss} = \lim_{s \to 0} sE(s) \tag{34}$$

We express $E(s)$ as

$$E(s) = Z(s) - R_z(s) \tag{35}$$

where $Z(s)$ is from (15) as

$$\begin{aligned} Z(s) = &\frac{m_0 C_z(s)}{m_0 C_z(s) + s^2(m_0+\delta_m)} R_z(s) \\ &+ \frac{m_0+\delta_m}{m_0 C_z(s) + s^2(m_0+\delta_m)} D_z(s) \\ &+ \frac{g\delta_m}{C_z(s) m_0 s + s^3(m_0+\delta_m)} \end{aligned} \tag{36}$$

Consider the following cases:

Case 1 : $R_z(s) \neq 0,\ D_z(s) = \delta_m = 0$ into (34).

By inserting (16) in to (36), we obtain e_{ss1} as follows

$$\begin{aligned} e_{ss1} &= \lim_{s\to 0} s\left[\frac{m_0 C_z(s)}{m_0 C_z(s) + s^3(m_0+\delta_m)} - 1\right]/s \\ &= \lim_{s\to 0} \frac{s^2(m_0+\delta_m)}{m_0\left[\frac{k_P}{\epsilon m_0} + \frac{k_I}{\epsilon^2 m_0 s} + \frac{k_D s}{\epsilon^3 m_0}\right] + s^2(m_0+\delta_m)} \\ &= 0 \end{aligned} \tag{37}$$

Case 2 : $D_z(s) \neq 0,\ R_z(s) = \delta_m = 0$.

We obtain e_{ss2} as follows

$$\begin{aligned} e_{ss2} &= \lim_{s\to 0} \frac{m_0}{m_0\left[\frac{k_P}{\epsilon m_0} + \frac{k_I}{\epsilon^2 m_0 s} + \frac{k_D s}{\epsilon^3 m_0}\right] + m_0 s^2} \\ &= \frac{m_0 \epsilon}{k_P} \end{aligned} \tag{38}$$

Case 3 : $\delta_m \neq 0,\ R_z(s) = D_z(s) = 0$.

We obtain e_{ss3} as follows

$$\begin{aligned} e_{ss3} &= \lim_{s\to 0} \frac{g}{m_0\left[\frac{k_P}{\epsilon m_0} + \frac{k_I}{\epsilon^2 m_0 s} + \frac{k_D s}{\epsilon^3 m_0}\right] + (m_0 + 1/s)s^3} \\ &= \frac{g\epsilon}{k_P} \end{aligned} \tag{39}$$

Therefore, the overall steady-state error is obtained by adding $e_{ss1} + e_{ss2} + e_{ss3}$ as

$$e_{ss} = 0 + \frac{m_0\epsilon}{k_P} + \frac{\geq \psi lon}{k_P} = \frac{(m_0+g)\epsilon}{k_P} \tag{40}$$

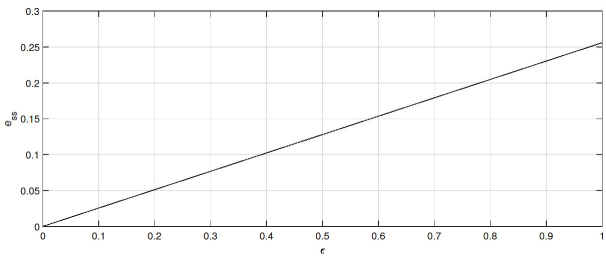


Fig. 5. Effect of ϵ steady-state error.

V. Experimental results

In this section we verify our control scheme by

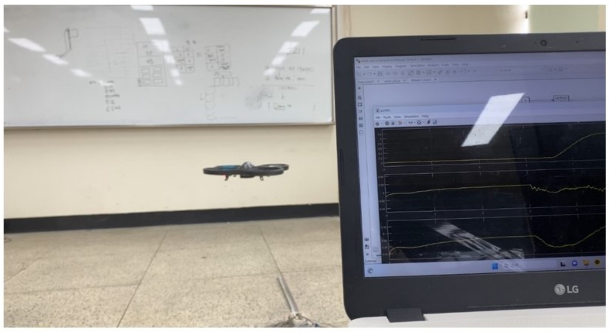


Fig. 6. Experimental set-up.

the experiment. The quadrotor used in the experiment is the AR Drone. The experimental set-up is shown in Fig. 6.

The experiments are conducted to show that our control method coincides with our analysis. The uncertain mass used in the experiment corresponds to no more than 5% of the nominal mass of the AR Drone which is $0.429kg$. The systems parameters are listed in Table. 3.

Table 3. Model parameters of the altitude of a quadrotor.

Parameters	Value	Units
m_0	0.429	kg
g	9.81	m/s^2

We carry out the experiment with different sets of $\epsilon-$PID parameters based on our analysis and we obtain similar output responses. The following are the absolute values of regulation error responses of the controller. The control input with $\epsilon \leq 0.7$ is not used due to the input saturation. Also, we can compare our method with traditional PID controller(ϵ=1) [12].

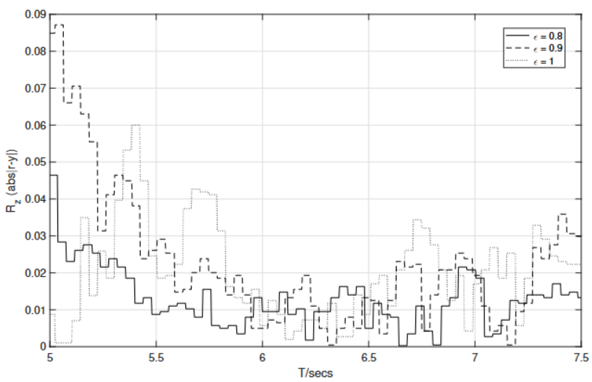


Fig. 7. Plots of $|r-y|[k_P(\epsilon), k_I(\epsilon), k_D(\epsilon)] = [6, 0.024, 2.5]$ for $5 \leq t \leq 7.5$.

Along with Fig. 7, we calculate the mean absolute values of error as follows in order to provide numerical results for easier reading.

$$ME = \sum_{i=0}^{2500} \frac{|r(5+\Delta i) - y(5+\Delta i)|}{2500} \tag{41}$$

Here, i are the number of sampled data. The ME values are obtained and compared in the table below.

Table 4. ME of the proposed controller with different values of ϵ.

ϵ	ME
0.8	0.88
0.9	2.6
1	4.9

As consistent with our analysis, ME indeed becomes smaller along with the decrease of ϵ. Thus, with experimental results, our validity of our control method is verified.

V. Conclusion

In this paper, we have proposed an $\epsilon-$PID controller for the $z-$altitude control of the quadrotor system. The robustness of the proposed controller is analytically and experimentally shown. Based on our analysis, the controller PID gain parameters k_P, k_I, k_D are first selected and then used to calculate the step response characteristics (w_n, ζ, M_p) We then have proceeded to select the gain-scaling parameter ϵ based on error analysis. We have confirmed the validity of our control method via the experimental results. In particular, we have shown that the use of ϵ considerably affects the control regulation error in hovering control of a quadrotor. Our current work will be extended to the robust trajectory-tracking control of a quadrotor in future.

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BIOGRAPHY

Alhassan Dodo Adamou Soudeize (Member)

2021 : BSC degree in Electrical and Electronic Engineering, Islamic University of Technology (IUT).
2023~present : MS degree in Electrical Engineering, Dong-A University.

Ji-Sun Park (Member)

2019 : BS degree in Electrical Engineering, Dong-A University.
2021 : MS degree in Electrical Engineering, Dong-A University.
2021~present : PhD degree in Electrical Engineering, Dong-A University.

Ho-Lim Choi (Member)

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