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Non Simultaneous Morphing System Design for Yaw Motion in Quadrotors

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Abstract

Quadrotors are unmanned aerial vehicles that are frequently used in military and civilian applications. In this study, the modeling, control and variable geometry of the quadrotor's yaw motion are discussed non simultaneous. Mathematical modeling and simulation of an unmanned air vehicle, specifically, quadrotor modeling is not an easy task because of its complex structure, non-lineardynamics and under-actuated nature. Quadrotor has a non-linner structure but the system has been converted to linear structure by using various methods. Linear expressions are expressed by state space model. Simulation was performed in Matlab / Simulink environment using state space model. PID algorithm was used as control system. In the simulations, both without morphing results and morphing results were obtained and compared. The main purpose of this study is to examine the effect of morphing on a quadrotor modeled as realistic as possible on yaw motion.

Keywords: Quadrotor, UAVs, morphing, state space model, PID, control, quadcopter, control system, motion control

1. Introduction

Quadrotor, vertical landing take-off, hanging in the air, high maneuverability, although complex as a control system, structurally simple, rotating wing unmanned aerial vehicle. In the last decade, interest in unmanned aerial vehicles(UAVs) and their design and control has exponentially increased[1], due to their capability to carry out several complex tasks, in addition to their low cost production and relatively simple operation[2]. Quadrotor is used in hobby, photography, agriculture, research in civil field. In the military field, it is used in many tasks such as reconnaissance, surveillance, port security and border security.

Morphing is generally referred to as changing the geometry of an aircraft before or during flight. In recent years, there have been many studies on quadrotor morphing. C. Hintz et al., in their work, made a design on the morphing of multirotors[3]. In this design, the multirotor had the capacity to pass through narrow spaces. Desbiez et al.[4] also made a study that changed the angle between the arms of a quadrotor. During the flight, a signal coming to the quadrotor and the arms would move at the intersection points and complete the morphing process. In tests with the so-called X-Morf aircraft, the quadrotor gave good stability and trajectory

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tracking performance. T. Oktay et. al.[5] conducted active and passive morphing studies on tactical unmanned aerial vehicles (TUAVs) on both longitudinal and lateral flights. They used the PID algorithm to control TUAVs and used the optimization method called stochastic approximation to determine the wing opening ratio. As a result of the tests, TUAVs followed the desired trajectory in both longitudinal and lateral flights.

In this study, it is about how the quadrotor affects the yaw movement while performing the active morphing process. At the end of the study, quadrotor modeling was done and compared with yaw motion in both morphing and non-morphing situations.

The quadrotor consists of four motors and propellers, each rotor produces a thrust[6]. The yaw motion is obtained from the counter torque between each of the propellers. While each rotor rotates at equal angular velocities, the net yaw is zero, but the speeds difference between the two pairs creates a positive or negative yaw. Forward or backward movement which is related to the pitch angle can be obtained by increasing the back rotor thrust and decreasing the front rotor thrust. Finally, a sideways motion which is related to the roll, φ angle can be achieved by increasing the left rotor thrust and decreasing the right rotor thrust. Figure 1 shows the various motions of a quadrotor due to changes in rotor speeds.

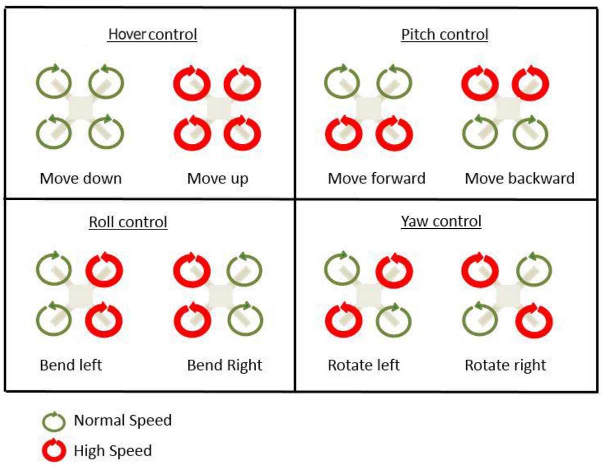

Figure 1. Quadrotor motion

In this article, yaw motion will be examined first by using PID control. Then, quadcopter morhing will be applied to discuss how this situation affects yaw movement.

2. Material and Methods

In this section, information about the quadrotor mathematical model and control system is given.

2.1 Quadrotor Dynamic Model

The dynamic model of quadrotor is obtained from Newton–Euler approach. Here, the Newton-Euler approach is used with the following assumptions[7, 8]:

- the structure is rigid and symmetric,
- the propellers are rigid,
- the thrust and the drag are proportional to the square of speed,
- ground effect is neglected.

Quadrotor used equations of lateral motion equations to make yaw motion. The nonlinear motion equations are as follows.

$$\begin{aligned} \dot{y} &= v[c(\phi)\,c(\psi) + s(\phi)\,s(\psi)\,s(\theta)] - w[c(\psi)\,s(\phi) - c(\phi)\,s(\psi)\,s(\theta) + u[c(\theta)\,s(\psi)]] \\ \dot{v} &= (wp - ur) - g\,c(\theta)\,s(\phi) \\ \dot{p} &= \frac{I_y - I_z}{I_x} qr + \frac{U_2}{I_x} \\ \dot{r} &= \frac{I_x - I_y}{I_z} pq + \frac{U_4}{I_z} \\ \dot{\phi} &= p + r[c(\phi)\,t(\theta)] + q[s(\phi)\,t(\theta)] \\ \dot{\psi} &= r\frac{s(\phi)}{c(\theta)} + q\frac{s(\phi)}{c(\theta)} \end{aligned} \tag{1}$$

Inputs must be applied to the system to control quadrotor movements. The torque difference between the propellers is used to realize each movement[9]. The input values and torques are proportional to the square of the rotors' speeds[10].

$$\begin{aligned} f_t &= U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ \tau_x &= U_2 = bl(-\Omega_1^2 - \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ \tau_y &= U_3 = bl(\Omega_1^2 - \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \\ \tau_z &= U_4 = d(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2) \end{aligned} \tag{2}$$

Where l the distance between any rotor and the center of the quadrotor, b is the thrust factor and d is the drag factor. Here, lift and drag factors of the propeller blade (b and d respectively) are calculated from the Blade Element Theory.

The inputs of motion equations are propeller speeds. U1, U2, U3 and U4 are related to throttle, roll, and picth and yaw respectively [11]. U4 is used for yaw motion input.

2.2 State Space Model and Morphing

A state-space representation is a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations or difference equations[12]. State variables are variables whose values evolve through time in a way that depends on the values they have at any given time and also depends on the externally imposed values of input variables. Output variables' values depend on the values of the state variables.

The state space model is a mathematical model of a system as a set of input, output, and state variables associated with the equation from the first order. The state space model is expressed as follows:

$$\dot{x} = Ax(t) + Bu(t)$$

$$y = Cx(t) + Du(t)$$

Where x(t) state vector, u(t) control or input vector, y(t) output vector, A system vector, B input vector, C output vector and D feed forward vector.

In order to obtain the state space model, it is necessary to bring the nonlinear equations in equation 1 into a linear state. The set of linearized equations is as follows:

$$\begin{aligned} \dot{y} &= v \\ \dot{v} &= g\phi \\ \dot{p} &= \frac{\tau_x}{I_x} \\ \dot{r} &= \frac{\tau_z}{I_z} \\ \dot{\phi} &= p \\ \dot{\psi} &= r \end{aligned} \quad (3)$$

$[y \quad \phi \quad \psi]^{T}$ the vector containing the linear and angular position of the quadrotor in the earth frame and $[v \quad p \quad r]^{T}$ the vector containing the linear and angular velocities in the body frame[13].

According to equation 3, the state space model for the yaw movement is as follows:

$$\begin{bmatrix} \dot{y} \\ v \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & g & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} y \\ v \\ p \\ r \\ \phi \\ \psi \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/I_x & 0 \\ 0 & 1/I_z \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tau_x \\ \tau_z \end{bmatrix}$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} y \\ v \\ p \\ r \\ \phi \\ \psi \end{bmatrix}$$

In the equations of motion I_x , I_y and I_z denotes the diagonal inertia matrix[14].

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \quad (4)$$

Researchers have long realized that birds can change their body positions during the flight to perform certain maneuvers and adjust their aerodynamic structures for the appropriate flight situation. This body shape has been termed 'morphing' in specific literature[15].

In this article, morphing is performed by changing the arm lengths geometrically. Quadrotor generally has two types of geometric structure. These:

- X style
- Plus(+) style

In this article, x style quadrotor is discussed.

Morphing has two types:

- Active morphing
- Passive morphing

If the quadrotor performs morphing in the air, it is called active morphing. If the quadrotor performs morphing before taking off on the ground, it is called passive morphing.

This article uses active morphing because the quadrotor performs morphing during flight.

Changing the arm geometry is shown in Figure 2 and Figure 3.

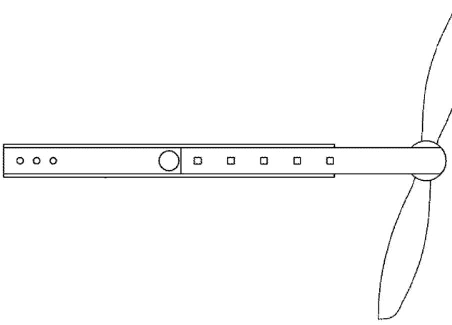

Figure 2. Normal arm length

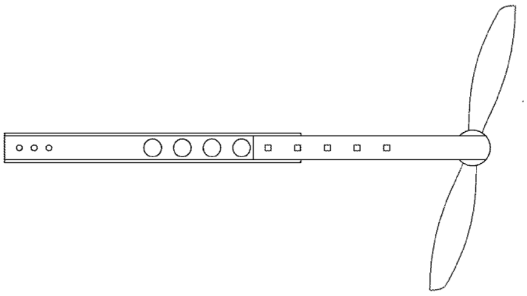

Figure 3. The extended arm (%10)

2.3 Quadrotor Control System

Proportional-Integral-Derivative (PID) control is the most common control algorithm used in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. PID algorithm was used for quadrotor control. The overall structure of the PID controller is like Figure 4.

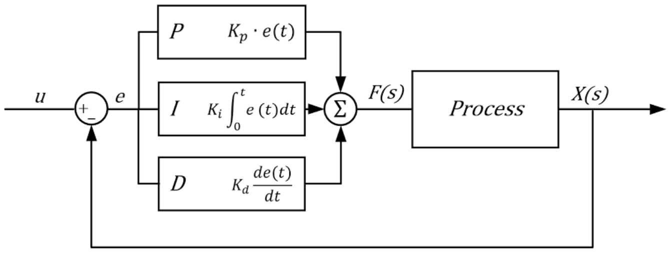

Figure 4. PID controller

PID controller output equation is as follows:

$$u(t) = K_p\, e(t) + K_i\, \int_0^t (t)d(t)\ + K_d\, de(t)/d(t) \qquad (4)$$

Where, K_p proportional gain, K_i integral gain and K_d is the derivative gain, e(t) the error caused by the difference between the reference and response of the system. The proportional gain is used to control the rise time of system response. The integral gain is used to eliminate steady-state error. The derivative gain allows reducing the amount of overflow and developing a transient response. The success of PID controller dependds on proper selection of gain parameters. Table 1 shows theeffect of such increased parameters on a controlled system.

Table 1. Effects of independent P,I and D tuning

Closed loop respone	Rise time	Overshoot	Settling time	Steady-state error	Stability
Increasing $\boldsymbol{k_p}$	Decrease	Increase	Small increase	Decrease	Degrade
Increasing $\boldsymbol{k_i}$	Small decrease	Increase	Increase	Large decrease	Degrade
Increasing $\boldsymbol{k_d}$	Small decrease	Decrease	Decrease	Minor change	Improve

According to this, the PID expression required for the yaw motion:

$$u(t) = K_{p\psi}e(t) + K_{i\psi} \int_0^t e(v)d(v) + K_{d\psi} \frac{de(t)}{d(t)} \qquad (5)$$

Accordingly, the quadrotor yaw motion PID block is as follows:

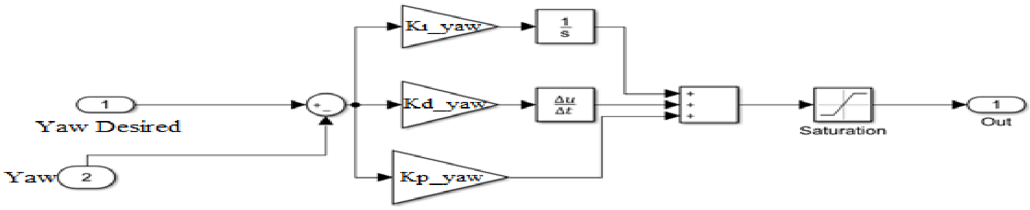

Figure 5. Yaw motion PID block

3. Results and Discussion

Figure 6 shows the case where quadrotor is not morphing. Figure 7 shows the case of morphing.

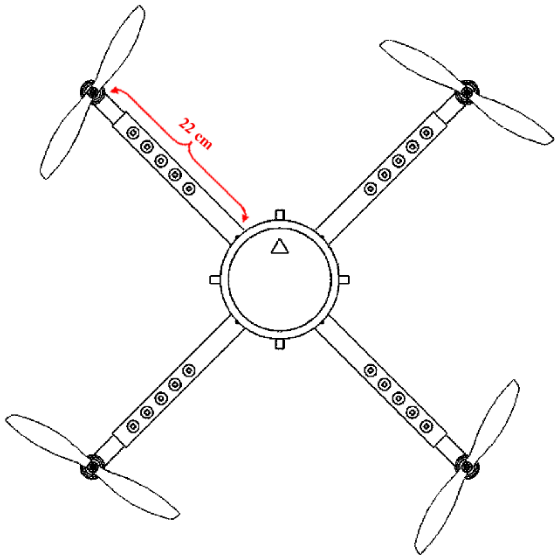

Figure 6. Without morphing

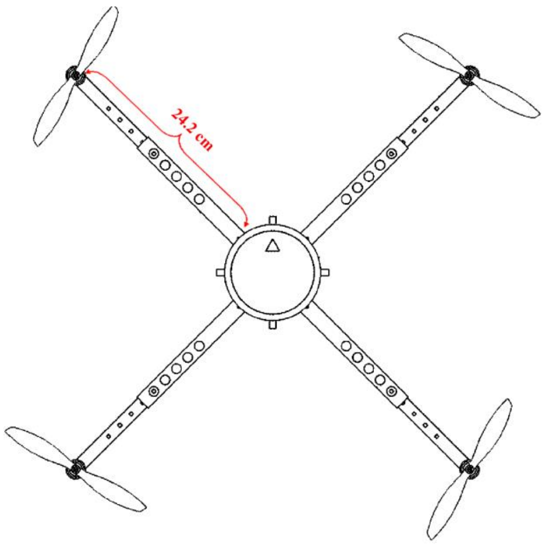

Figure 7. Quadrotor morphing

The inertia moment is affected when the quadrotor is moprhing during flight[16]. Because morphing is the change of arm lengths.

When the arm length is ΔL = 22 cm, inertia moment and other characteristics of the quadrotor are given in Table 2.

Table 2. Quadrotor data without morphing

QUADROTOR	
R_{plate}	6.20 cm
M_{plate}	20 gr
M_{arm}	40 gr
M_{motor}	20 gr
$M_{quadrotor}$	820 gr
L	22 cm
b	$1.0741x10^{-7}$
d	$1.8099x10^{-9}$
C_d	2.6
Ix	0.089
Iy	0.089
Iz	0.0177

Quadrotor morphing was performed when the arm length was ΔL = 24.2 cm. In this case, inertia moment and other characteristics of the quadrotor are given in Table 3.

Table 3. Quadrotor data morphing state

QUADROTOR	
R_{plate}	6.20 cm
M_{plate}	20 gr
M_{arm}	40 gr
M_{motor}	20 gr
$M_{quadrotor}$	820 gr
L	24.2 cm
b	$1.0741x10^{-7}$
d	$1.8099x10^{-9}$
C_d	2.6
Ix	0.091
Iy	0.091
Iz	0.018

Yaw flight Simulink model is as follows:

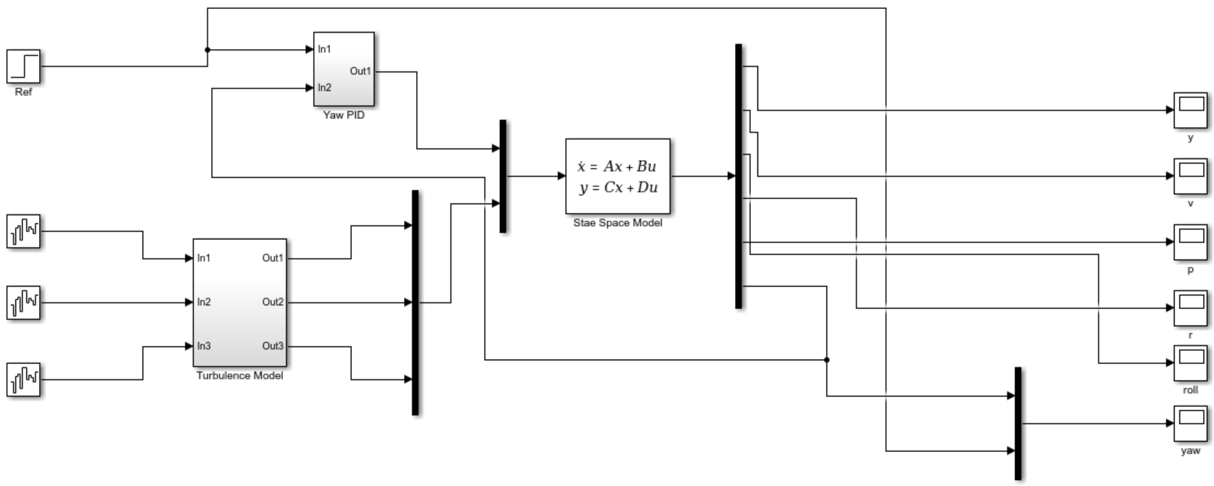

Figure 8. Yaw flight simulink model

In yaw flight, the PID coefficients remain the same in both the non-morphing and morphing states. The following table shows the PID coefficients.

Table 4. PID coefficients

P	I	D
0.5	0.5	0.5

The simulation result without morphing is shown below.

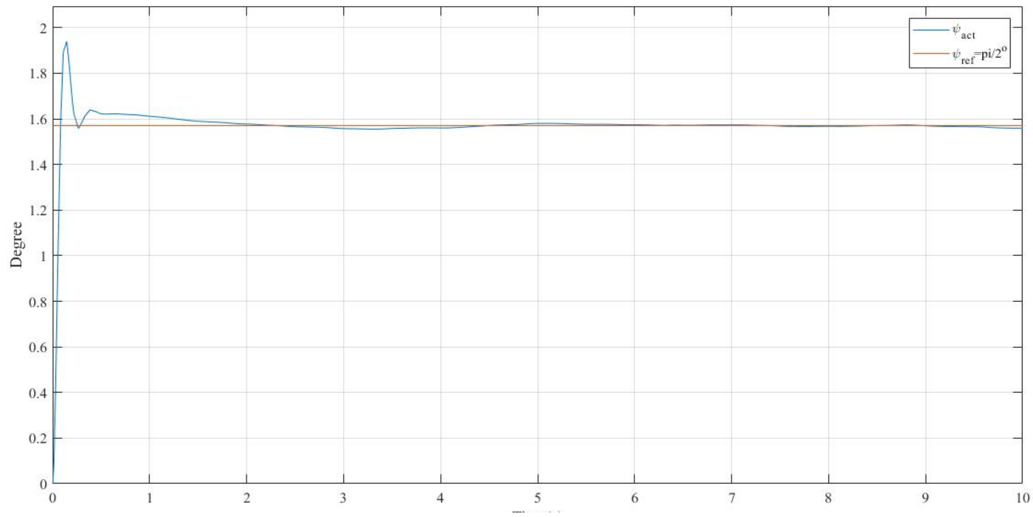

Figure 9. Simulation result without morphing

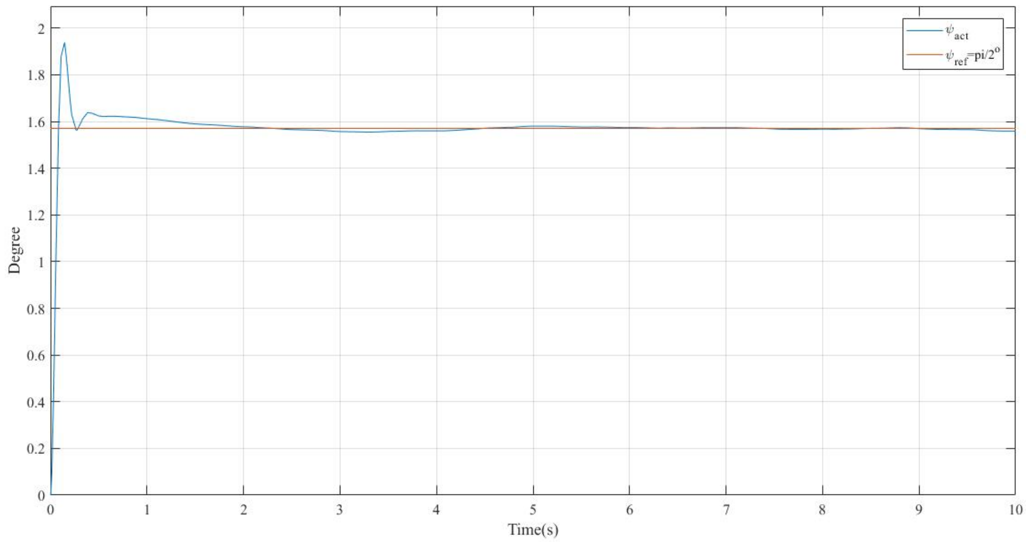

Figure 10. Morphing simulation result

4. Conclusions

In this study, non simultaneous morphing system desings for quadrotors was discussed. Also, the morphing situation during quadrotor yaw flight is discussed. The quadrotor dynamic model was obtained by using Newton Euler equations. The Von Karman Turbulence Model was used as an aerodynamic side effect on the quadrotor movement. The PID algorithm was used to control the quadrotor.

Morphing has affected the yaw flight. This situation can be seen both from the simulation result and from the following rise time, settling time and overshoot values.

The following tables show the rise time, settling time and overshoot values without morphing and morphing.

Table 5. Yaw flight system characteristic

	L=22 cm(No morphing)	L=24.2 cm(%10 morphing)
Rise Time	0.0559 second	0.0566 second
Settling Time	1.16 second	1.18 second
Overshoot	24.7 %	24.4 %

In future studies, PID coefficients and morphing amount will be determined using optimization algorithms. This will improve the design performance criteria and allow the quadrotor to fly more stable and performance.

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