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# Investigation of the Effect of Differential Morphing on Forward Flight by Using PID Algorithm in Quadrotors

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**Abstract**

In this study, modeling, control and differential morphing of a four-rotor unmanned aerial vehicle known as a quadrotor is discussed. With differential morphing, the forward flight performance and model of an autonomous quadrotor is presented. Due to the complex structure of the quadrotor, it is difficult to build the model. To get model parameters, a complete quadrotor model is drawn in the Solidworks program. In addition, Newton-Euler equations are used in the mathematical model. Simulation is done in Matlab / Simulink environment by using the parameters obtained from the model and the state-space model approach. PID (proportional, integral, derivative) is used as the quadrotor control algorithm. As a result of the study, the quadrotor forward flight is carried out using PID algorithm and differential morphing. The system characteristics of the situations with and without differential morphing are compared and the results are presented with graphs.

***Keywords:*** Quadrotor, Morphing, PID, State Space Model, Control

## 1. Introduction

In the past two decades, unmanned aerial vehicle(UAV) have had a major impact in the aviation field. A UAV is defined as a powerful aircraft that does not carry a flight crew, can be managed autonomously or remotely and can be reused. UAVs are preferred because they eliminate the risk of living people in dangerous situations such as search and rescue, military operations and fire fighting. It is highly valuable as it is used in these dangerous missions without direct human access.

The UAV type quadrotor discussed in this study is a small rotary wing unmanned aerial vehicle capable of vertical takeoff and landing. Although the quadrotor is structurally simple, it is complex as a control system. Quadrotor is used in civilian areas such as photography and cinema, agricultural activities, hobbyism. It is also used in military areas such as reconnaissance, coast and port security.

Morphing, which is considered within the scope of this study, is defined as the changes that occur in the geometry of the quadrotor flight or before the

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flight. There have been many studies on quadcopter morphing in recent years. C. Hintz et al.[1] performed morphing on a H-type quadrotor. This quadrotor is designed to pass through narrow spaces in vertical flight. In real-time applications, quadrotor successfully accomplished this operation.

A. Desbiez et al.[2] worked on the X-Morf quadrotor, which changed its geometry during flight. This quadrotor could change the position of the arms with servo motors. As a result of the tests, it was revealed that 28.5% performance was dynamically increased in the range of 0.5s during the flight. T. Avant et al.[3] did a study on quadrotor arm rotation and enlargement. Quadrotor motors could not turn more than half. Its arms could expand by 25%. D. Falanga et al. [4] designed a quadrotor capable of crossing narrow spaces. This quadrotor was able to trajectory tracking within a plan. As a result of the test studies, it was able to pass 80% succession through narrow angled areas up to 45 degrees. Y. Bai [5] worked on a quadrotor that changed its geometry during flight. It revealed that the lateral control and stability of the quadrotor after morphing was weakened. T. Oktay and S. Coban[6] have worked on a Tactical Unmanned Aerial Vehicle (Tuavs) that includes both active and passive morphing for simultaneous longitudinal and lateral flight. In this study, they used simultaneous perturbation stochastic approximation (SPSA) as an optimization algorithm. As a control algorithm, they used proportional integral derivative (PID). T. Oktay and S. Coban[7] applied active and passive morphing for lateral movement on TUAV. They created the TUAV model in Matlab / Simulink environment. They used the state space model approach for modeling. Morphing process was carried out from TUAV wing tips and the wings could lengthen and shorten by 40 cm. They used the SPSA method to determine the amount of morphing. They saved up to 8% energy with the SPSA method.

In this study, the effect of differential morphing quadrotor forward flight was investigated. Quadrotor mathematical model was created in the first stage. Model parameters such as mass and inertia were then taken from the full model drawn in the Solidworks program. In the third stage, quadrotor state space model is created. As a result, quadrotor forward flight simulations with and without morphing were performed and simulation parameters such as rise time, overshoot and settling time were compared.

## 2. Material and Methods

As shown in Figure 1, the quadrotor consists of four rotors and propellers, and each rotor produces thrust.

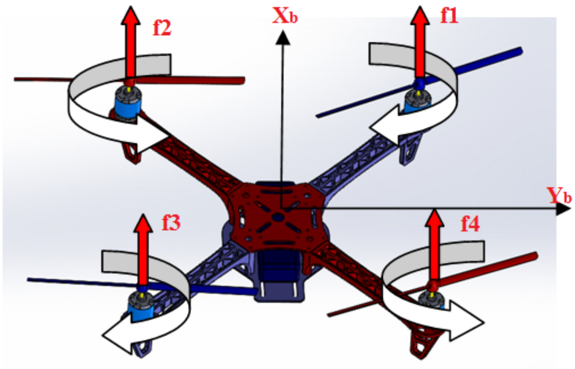


**Figure 1.** Quadrotor

When the total thrust force generated by the rotors is greater than the weight of the quadrotor, the quadrotor starts to take off. In order for the quadrotor to forward flight, it must reduce the speed of the front rotors and increase the speed of the rear rotors. Quadrotor forward flight is on the y axis. Quadrotor forward flight and rotation direction of rotors are shown in figure 2.

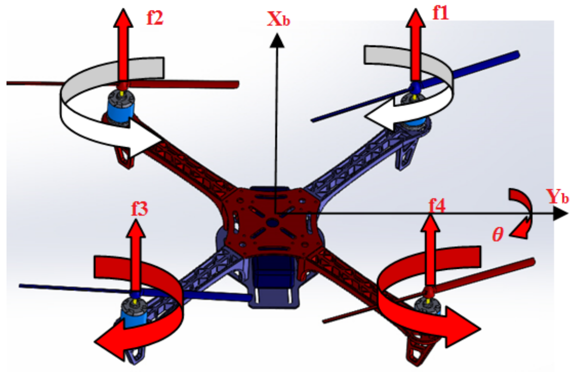


**Figure 2.** Quadrotor forward flight

### 2.1 Quadrotor Dynamic Model

Newton-Euler approach is used for the Quadrotor dynamic model. The following views are valid in the Newton-Euler approach[8, 9].

- Quadrotor structure is rigid and symmetrical,
- Propellers of quadrotor are rigid,
- Quadrotor thrust and drag force are proportional to the rotor speed square,
- Ground effect in the quadrotor is neglected.

The quadrotor dynamic model has twelve total motion equations that provide motion. These equations have a non-linear structure. These equations are made linear using various linearization methods. In this study, linear motion equations are studied. Twelve equations of motion are divided into two parts. The first part is used for longitudinal (forward flight) flight. The second part is used for lateral flight. Forward flight equations are given below.

$$\dot{x} = u$$

$$\dot{z} = w$$

$$\dot{u} = -g\theta$$

$$\dot{w} = \frac{f_t}{m} \tag{1}$$

$$\dot{q} = \frac{\tau_y}{I_y}$$

$$\dot{\theta} = q$$

Where, x, z and $\theta$ are linear and angular positions. u, w and q are linear and angular velocity.

Inputs must be applied to the system to control the quadrotor. These inputs tell how far the quadrotor will fly forward in the simulation. Accordingly, the input to be applied for forward flight is given below.

$$\tau_y = bl(\Omega_1^2 - \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \tag{2}$$

Where l the distance between any rotor and the center of the quadrotor, b is the thrust factor, $\Omega$ is propeller speed.

### 2.2 State Space Model and Differential Morphing

State space model is the expression of a physical system in first order differential equations with input, output and state variables in matrix form. Quadrotor state space model is expressed by linear motion equations. In general, the state space model of a system is indicated by the following expression.

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

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

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

In this case, the quadrotor forward flight state space model would be as shown below.

$$\begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -g \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ z \\ u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1/m & 0 \\ 0 & 1/I_y \\ 0 & 0 \end{bmatrix} \begin{bmatrix} f_t \\ \tau_y \end{bmatrix}$$

$$y = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ z \\ u \\ w \\ q \\ \theta \end{bmatrix}$$

The state space model represents the $I_y$ inertia moment in the input matrix. Inertia moment is a diagonal matrix. This matrix is produced because the quadrotor's four arms are symmetrical and aligned on the x and y axes. The inetia matrix is as shown below.

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \tag{3}$$

The researchers noticed many years ago that birds changed their body positions and geometries to perform certain maneuvers during flight. This process of changing shape or geometry is called 'morphing' in the literature.

Morphing is a developmental feature that has just started to be used in unmanned aerial vehicle. This feature is related to UAV structure and aerodynamics, and UAV requires using effective control structures to control it quickly and stably[10]. In quadrotor type unmanned aerial vehicles, morphing is done by lengthening and shortening the arms or changing the angles between the arms. In the differential morphing system discussed in this study, the quadrotor forearms are extended while the back arms are either fixed or shortened. The front and back arms do not extend or shorten at the same rate.

### 2.3 Quadrotor Control Systems

For PID controller design, parallel architecture has been used[11].

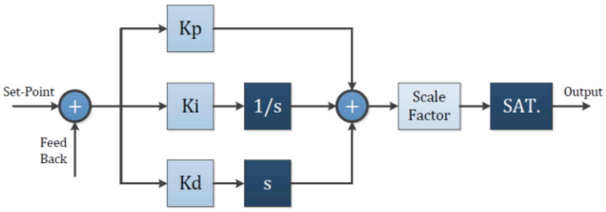


**Figure 3.** PID architecture

In the diagram, there is an additional block corresponding to a scale factor, which compensates the aerodynamic parameters of the quadcopter so that the PID design becomes simpler. This block also scales the control signal to values compatible with the existing hardware. Finally, at the output there is a signal saturation block. Pitch controllers have a similar architecture with minimal changes.

## 3. Results and Discussion

As this study deals with forward flight, differential morphing is created by lengthening or shortening the arms at different times. Since the quadrotor volume changes during the morphing process, there are changes in the moments of inertia. Since the quadrotor volume changes during the morphing process, there are changes in the moments of inertia. The quadrotor non-morphing state in Figure 4 and the inertia and mass information of this state in Table 1.

**Figure 4.** Non-morphing quadrotor

**Table 1.** Mass and moment of inertia information (non-morphing)

| m (kg) | Ix ($kg*m^2$) | Iy($kg*m^2$) | Iz($kg*m^2$) |
|---|---|---|---|
| 0.59 | 0.04085 | 0.01629 | 0.05607 |

If the forearms are extended by 3 cm while the mass remains constant, the quadrotor will be as shown in Figure 5 and information on mass and inertia is given in Table 2.

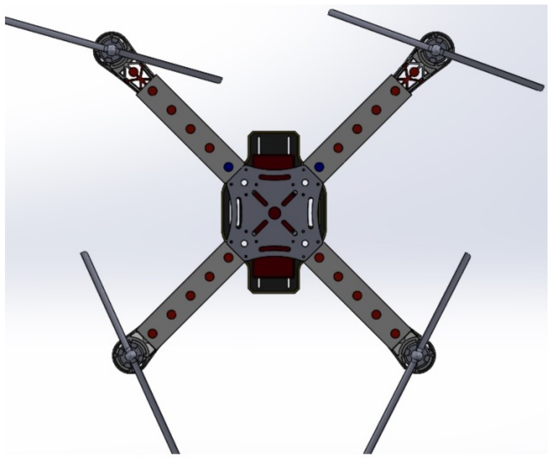

**Figure 5.** Differential morphing 1

**Table 2.** Mass and moment of inertia information(Differential morphing 1)

| m (kg) | Ix ($kg*m^2$) | Iy($kg*m^2$) | Iz($kg*m^2$) |
|---|---|---|---|
| 0.59 | 0.03859 | 0.00668 | 0.04418 |

Depending on the initial situation, if the forearms are extended by 6 cm, the quadrotor will be as shown in Figure 6 and mass and inertia information is given in Table 3.

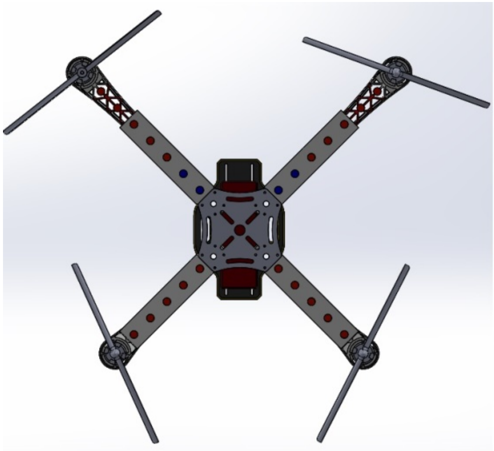

**Figure 6.** Differential morphing 2

**Table 3.** Mass and moment of inertia information(Differential morphing 2)

| m (kg) | Ix (kg*m$^2$) | Iy(kg*m$^2$) | Iz(kg*m$^2$) |
|---|---|---|---|
| 0.59 | 0.03851 | 0.00740 | 0.04483 |

PID coefficients for forward flight were chosen same values for both non-morphing and morphing cases. These values are given below.

**Table 4.** PID coefficients

| P | I | D |
|---|---|---|
| 0.0003 | 0.0003 | 1 |

Matlab simulation graphs of non-morphing state, differential morphing 1 and differential morphing 2 states provided that the mass remains constant are given below.

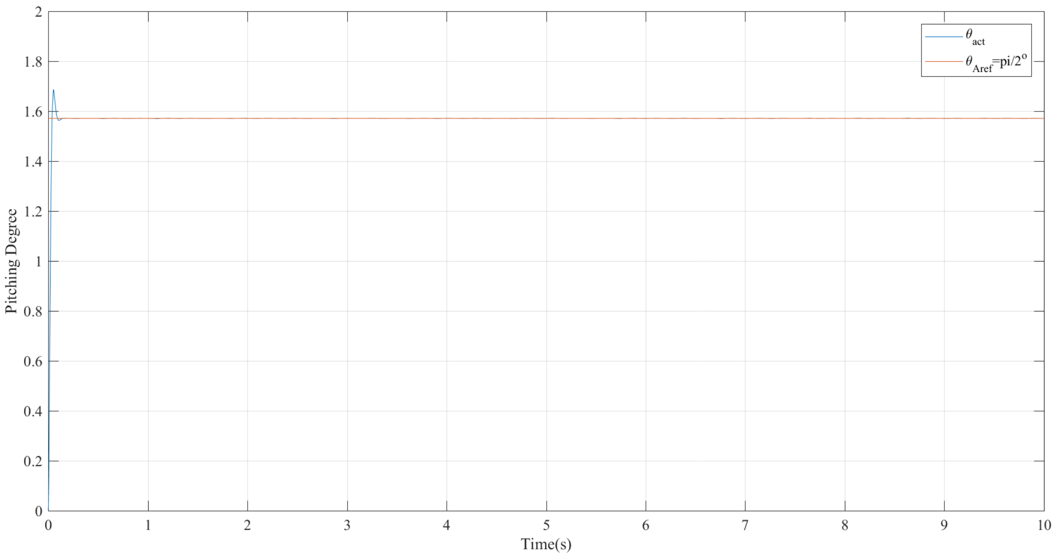


**Figure 7.** Non-morphing simulation

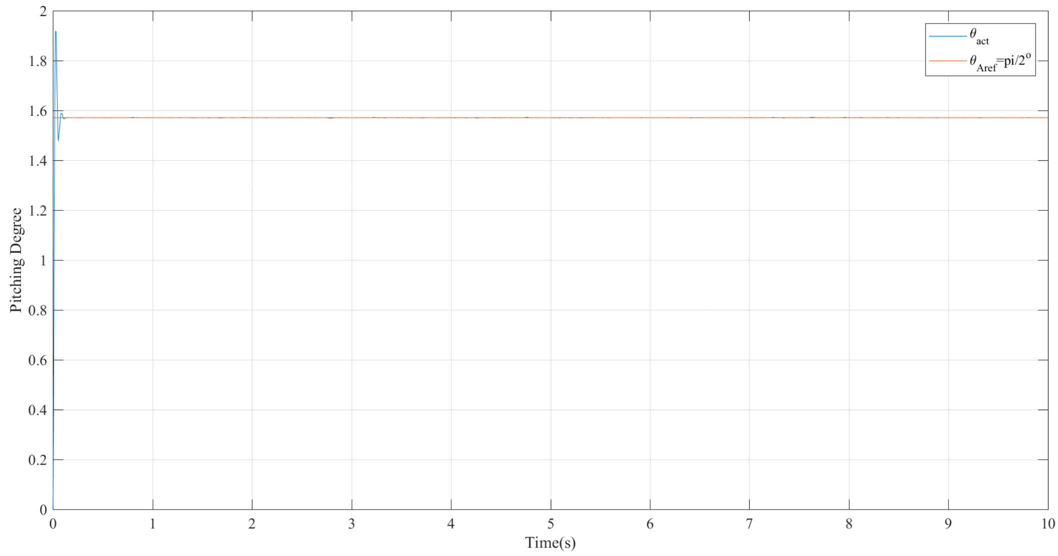


**Figure 8.** Differential morphing 1 simulation

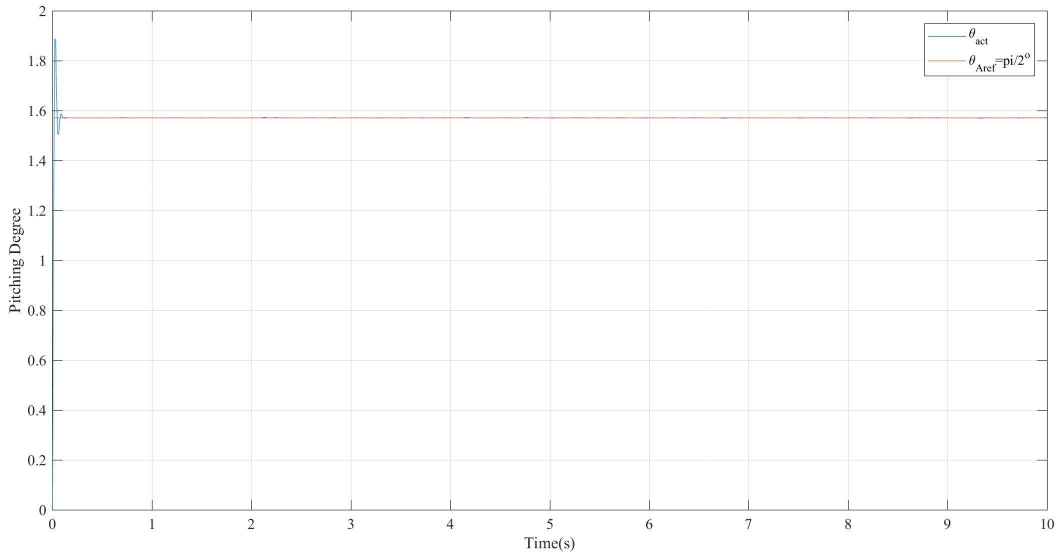


**Figure 9.** Differential morphing 2 simulation

## 4. Conclusions

In this study, the effect of differential morphing on forward flight in quadrotor was investigated. In addition, quadrotor modeling was also performed. The quadrotor dynamic model was created using the Newton-Euler approach.

The full quadrotor model was drawn using the Solidworks program. It was simulated in Matlab / simulink environment with the parameters taken from the model. PID algorithm is used as the Quadrotor control algorithm.

According to the simulation results, differential morphing affected the quadrotor forward flight. Design performance criteria such as rise time, settling time and overshoot have changed in the case of differential morphing. As shown in Table 5, differential morphing influenced design performance criteria. Despite the increase in overshoot of these criteria, rise time and settling time decreased. This made the quadcopter fit into orbit in less time. Sitting in orbit in a short time is a positive situation for the quadrotor.

**Table 5.** System characteristic

| | Non-morphing | Diferantial morphing 1 | Diferantial morphing 2 |
|---|---|---|---|
| Rise Time | 0.0249 | 0.0121 | 0.013 |
| Settling Time | 0.0766 | 0.0687 | 0.0721 |
| Overshoot | 7.39% | 24.5% | 22.4% |

**Ethical Approval**

Not applicable.

**References**


**[1]** C. Hintz, C. Torno, and L. R. G. Carrillo, "Design and dynamic modeling of a rotary wing aircraft with morphing capabilities," in *2014 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2014: IEEE, pp. 492-498.

**[2]** A. Desbiez, F. Expert, M. Boyron, J. Diperi, S. Viollet, and F. Ruffier, "X-Morf: a crash-separable quadrotor that morfs its X-geometry in flight," in *2017 Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS)*, 2017: IEEE, pp. 222-227.

**[3]** T. Avant, U. Lee, B. Katona, and K. Morgansen, "Dynamics, Hover Configurations, and Rotor Failure Restabilization of a Morphing Quadrotor," in *2018 Annual American Control Conference (ACC)*, 2018: IEEE, pp. 4855-4862.

**[4]** D. Falanga, E. Mueggler, M. Faessler, and D. Scaramuzza, "Aggressive quadrotor flight through narrow gaps with onboard sensing and computing using active vision," in *2017 IEEE international conference on robotics and automation (ICRA)*, 2017: IEEE, pp. 5774-5781.

**[5]** Y. Bai, "Control and Simulation of Morphing Quadcopter," Saint Louis University, 2017.

**[6]** T. Oktay and S. Coban, "Simultaneous longitudinal and lateral flight control systems design for both passive and active morphing TUAVs," *Elektronika ir Elektrotechnika,* vol. 23, no. 5, pp. 15-20, 2017.

**[7]** T. Oktay and S. Coban, "Lateral autonomous performance maximization of tactical unmanned aerial vehicles by integrated passive and active morphing," *International Journal of Advanced Research in Engineering,* vol. 3, no. 1, pp. 1-5, 2017.

**[8]** A. Marks, J. F. Whidborne, and I. Yamamoto, "Control allocation for fault tolerant control of a VTOL octorotor," in *Proceedings of 2012 UKACC International Conference on Control*, 2012: IEEE, pp. 357-362.

**[9]** S. Bouabdallah, "Design and control of quadrotors with application to autonomous flying," Epfl, 2007.

**[10]** C. Barbu, R. Reginatto, A. Teel, and L. Zaccarian, "Anti-windup design for manual flight control," in *Proceedings of the 1999 American Control Conference (Cat. No. 99CH36251)*, 1999, vol. 5: IEEE, pp. 3186-3190.

**[11]** K. J. Åström and T. Hägglund, *Control PID avanzado*. Pearson, Madrid, 2009.