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***Research Article***

# Quadrotorlar için Eş Zamanlı Olmayan Başkalaşım Tasarımı

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**Öz**

Quadrotor ticari, askeri ve dış mekân uygulamalarında yaygın olarak kullanılan dört rotorlu insansız hava aracı türüdür. Bu çalışmada quadrotor'un boylamasına ve yanlamasına olan uçuşunun modellemesi, kontrolü ve uçuş sırasındaki geometri değişimi ile başkalaşım durumu ele alındı. Başkalaşım işlemi boylamasına ve yanlamasına uçuşta aynı anda gerçekleşmemektir. Quadrotor uçuş sırasındaki geometri değişimi ya da uçuştan önce yerde iken meydana gelen geometri değişimi başkalaşım olarak ifade edilir. Quadrotor türü insansız hava araçlarında kolların uzayıp kısalması ve kol kesişim açılarının değiştirilmesi gibi çeşitli başkalaşım türleri vardır bu başkalaşım türlerine çalışmada yer verildi. Quadrotor yapısal olarak basit olmasına rağmen kontrol yapısı olarak zor ve karmaşık bir sistemden oluşur. Quadrotor matematiksel modeli non-lineer bir yapıya sahiptir. Bu yapı kullanılarak quadrotor kontrolü sağlanabilir fakat bu çalışma kapsamında lineer olmayan yapı çeşitli yöntemler kullanılarak lineer duruma getirildi. Lineer ifadeler çeşitli giriş ve çıkışlar kullanılarak durum uzay modeli yaklaşımı ile ifade edildi. Dinamik modelin elde edilmesinde quadrotor sistemlerinde yaygın olarak kullanılan Newton Euler metodu kullanıldı. Durum uzay modeli kullanılarak sistemin simülasyonu Matlab / SIMULINK ortamında gerçekleştirildi. Matlab / SIMULINK için gerekli olan parametreler ve sistemin grafiksel çizimi ise CAD programında yapıldı. Bu programdan kütle, atalet gibi parametreler elde edildi. Sistemin kontrolünde ise yaygın olarak kullanılan PID algoritması kullanıldı. Kontrol sistemi için gerekli olan Kp, Ki ve Kd gibi katsayılar ise deneysel olarak elde edildi. Von Karmana Türbülans modeli quadrotor belirli bir gürültü altında yükselme, boylamasına, yanlamasına ve yörünge izleme işlemleri için kullanıldı. Bu çalışmanın sonucu olarak eş zamanlı olmayan morphing ile boylamasına ve yanlamasına uçuş belirli bir gürültü altında PID kontrol algoritması kullanılarak gerçekleştirilmiş ve sonuçlar grafikler ile ortaya konulmuştur.

**Anahtar Kelimeler:** Quadrotor, Quadcopter, Başkalaşım, Durum uzay modeli, Insansız hava aracı, PID, Kontrol

# Non Simultaneous Morphing System Desing for Quadrotors

**Abstract**

Quadrotor is a four-rotor unmanned aerial vehicle which is widely used in commercial, military and outdoor applications. Non simultaneous morphing system desings for quadrotors was discussed. The morphing process does not occur at the same time in longitudinal and lateral flight. The geometry change during the quadrotor flight or the geometry change that occurred on the ground before the flight is expressed as the morphing. There are various types of morphing in quadrotor unmanned aerial vehicles such as elongation and elongation of the arms and changing the angle of the arm. These types of morphing are included in the study. Although the quadrotor is structurally simple, it consists of a difficult and complex system as a control structure. The quadrotor mathematical model has a non-linear structure. Quadrotor control can be achieved by using this structure, but in this study, the nonlinear structure is linearized by various methods. Linear expressions were with the approach of the state space model using various inputs and outputs.

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Newton Euler method, which is widely used in quadrotor systems, was used to obtain dynamic model. Simulation of the system using state space model was performed in Matlab / SIMULINK environment. The necessary parameters for Matlab / SIMULINK and the graphical drawing of the system were performed in CAD program. From this program parameters such as mass, inertia were obtained. In the control of the system, commonly used PID algorithm was used. The coefficients such as Kp, Ki and Kd required for the control system were obtained experimentally. Von Karman Turbulence model quadrotor was used for hover, longitudinal, lateral and trajectory tracking under a certain noise. As a result of this study, longitudinal and lateral flight was performed by using PID control algorithm under a certain noise and the results were presented by graphs.

**Keywords:** Quadrotor, Quadcopter, Morphing, State space model, Unmanned aerial vehicle, PID, Control, Non simultaneous morphing

# 1. Giriş

Quadrotor is a highly maneuverable four-rotor unmanned aerial vehicle (UAV) capable of vertical landing and take-off. Although the quadcopter is structurally simple, the control system is complex(Kose & Oktay, 2019). Quadrotor-type four-rotor unmanned aerial vehicles can be used in exploration, search, rescue, photography, mapping, agriculture, military services(Çoban & Oktay, 2018) and dangerous and space limited for human beings(Kumar & Michael, 2012; Mellinger, Shomin, & Kumar, 2010).

In recent years, many studies have been carried out on quadrotor type unmanned aerial vehicles. C. Hintz et. al.(Hintz, Torno, & Carrillo, 2014) in his study, introduced a multirotor capable of morphing. The intended system is capable of vertical flight, in contrast to traditional multirotor. With this system, the aim is to switch vertically from narrow areas. The multirotor presents the horizontal and vertical configuration model, and the author has shown it in an animation.

In A. Desbiez et. al.(Desbiez et al., 2017), a multirotor did a study that changed the angle between the two arms. During the flight, the multirotor arm sends signals to the junction points and changes the angle between them. The tests performed with the X-Morf robot showed that it is able to decrease and increase its span dynamically by up to 28.5% within 0.5s during flight while giving good stability and attitude tracking performances.

In G. Barbaraci(Barbaraci, 2015), he discussed the modeling and control of a multirotor with a variable geometric arm. The arm performs morphing by increasing or decreasing its angle with the Y axis. The multirotor control system uses LQR control and PID control as well.

In Gibiansky(Gibiansky, 2012), the multirotor tests the multirotor designed with simulation by changing the geometry and control parameters. Evaluate simulation results and parameters obtained from experimental flights.

T. Oktay and O. Kose(Oktay & Kose, 2019a, 2019b, 2019c), an X-type multirotor, applies morphing to both hover, longitudinal and lateral flight. Morphing multirotor arm with elongation and shortening takes place. The morphing parameters are evaluated in flight in the hover and longitudinal. According to the simulation results, morphing takes place successfully and there is no change in multirotor performance and stability.

T. Oktay and S. Coban(Oktay & Coban, 2017), in their study, discussed the simultaneous both longitudinal and lateral morphing tactical unmanned aerial vehicle. In order to obtain the morphing parameters, they applied simultaneous perturbation stochastic approximation (SPSA).

# 2. Materials and Methods

## 2.1. Introduction of Quadrotor Movements

The quadrotor consists of four motors and propellers. Each rotor produces a thrust. If the total thrust produced by the four-rotor is equal to the weight of the quadrotor, the quadrotor will remain in the air hover. As shown in Figure 1, the rotor pairs (1-3, 2-4) are opposite to each other but the pairs rotate in the same direction. If the quadrotor moves in the vertical axis, the revolutions of all the rotors must be increased evenly and reduced. If the rotor revolutions are increased by the equal amount, the total thrust produced will be greater than the quadrotor weight and the quadrotor will be accelerated upwards. If the rotor revolutions are reduced by an equal amount, the total thrust produced will be less than the weight of the quadrotor, so the acceleration will decrease and the quadrotor will start to descend.

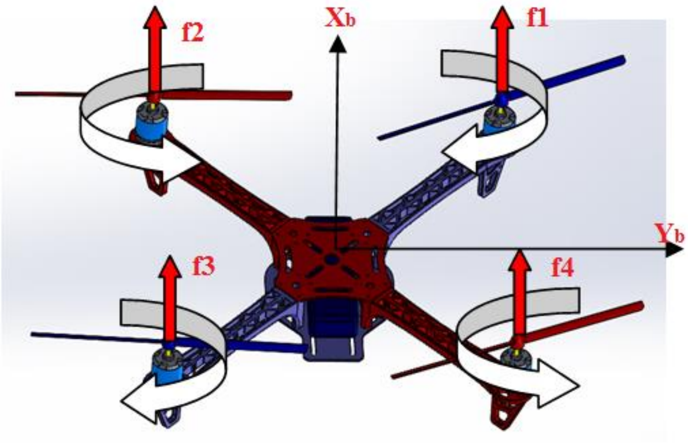


*Figure 1: Quadrotor*

As in Figure 2, the speeds of the rotors 2 and 3 should be increased and the speeds of the rotors 1 and 4 should be reduced in order to roll($\phi$) the quadcopter X axis.

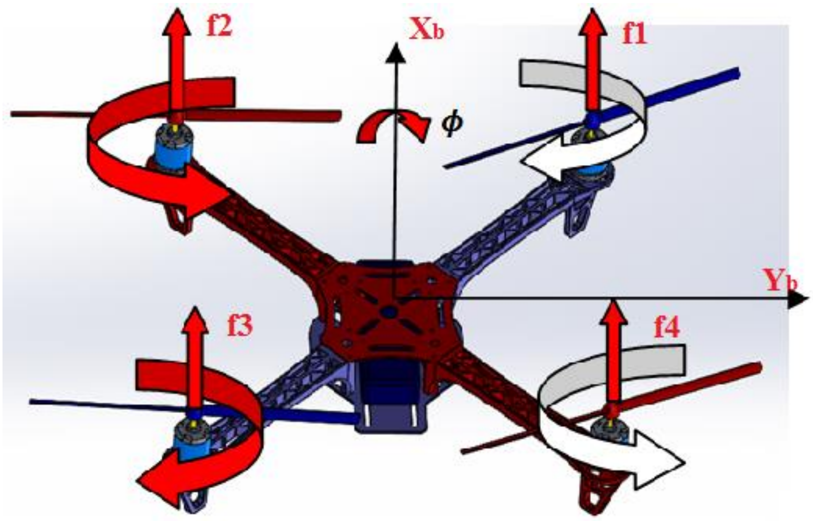


*Figure 2: Roll Motion*

As in Figure 3, the speeds of the rotors 3 and 4 should be increased and the speeds of the rotors 1 and 2 should be reduced in order to make the pitch(θ) movement of the quadrotor in the Y axis. In this case quadrotor will move forward.

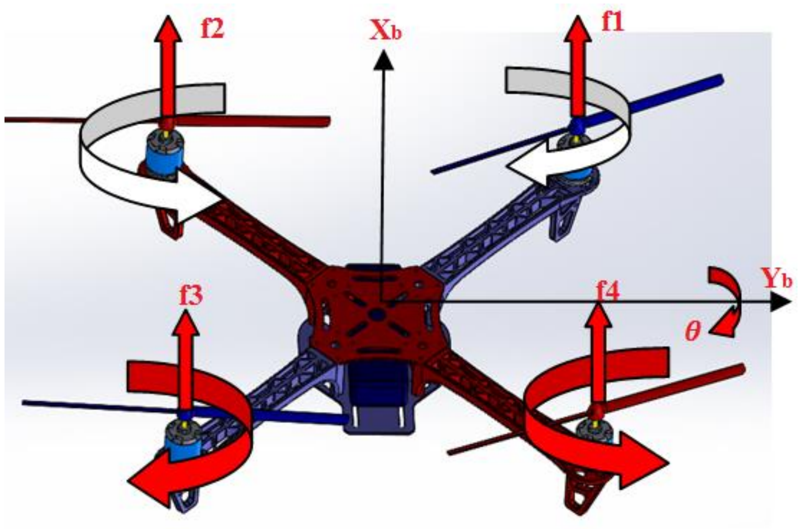


*Figure 3: Pitch Motion*

As in Figure 4, it is necessary to increase or decrease the speeds of the co-rotors simultaneously to perform the yaw($\psi$) movement. When the rotor speeds 2 and 4 are increased and the rotor speeds 1 and 3 are reduced, the yaw movement takes place.

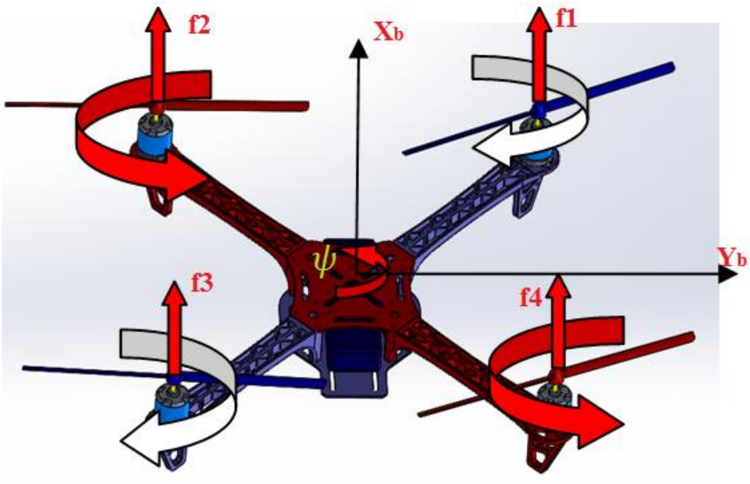


*Figure 4: Yaw Motion*

## 2.2. Quadrotor Dynamic Model

The Newton Euler approach is used to obtain quadrotor motion equations. In this approach, the following opinions apply(Marks, Whidborne, & Yamamoto, 2012).

- 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,

The equations used for the lateral flight are as follows:

$$\left.\begin{aligned} \dot{x} &= u \\ \dot{z} &= w \\ \dot{u} &= -g\theta \\ \dot{w} &= \frac{f_t}{m} \\ \dot{q} &= \frac{\tau_y}{I_y} \\ \dot{\theta} &= q \end{aligned}\right\} \quad (1)$$

The equations used for the lateral flight are as follows:

$$\left.\begin{aligned} \dot{y} &= v \\ \dot{v} &= g\phi \\ \dot{r} &= \frac{\tau_z}{I_z} \\ \dot{p} &= \frac{\tau_y}{I_y} \\ \dot{\phi} &= p \\ \dot{\psi} &= r \end{aligned}\right\} \quad (2)$$

From these equations x, y, z and $\phi$, θ, $\psi$ quadcopter holds the linear and angular position. u, w, q, v, p and r hold the linear and angular velocities.

In the equations of motion $I_x$ , $I_y$ and $I_z$ denotes the diagonal inertia matrix(Domingue, 2009; Sabatino, 2015):

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \quad (3)$$

The mathematical expression of the input forces of quadrotor is as follows:

$$
\begin{aligned}
f_t &= U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\
\tau_x &= U_2 = bl(-\Omega_1^2 - \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\
\tau_y &= U_3 = bl(\Omega_1^2 - \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \\
\tau_z &= U_4 = d(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2)
\end{aligned} \tag{4}
$$

The inputs of motion equations are propeller speeds. U1, U2, U3 and U4 are related to throttle, roll, picth and yaw respectively(Bresciani, 2008). For lateral flight, U2 input is used. Where l the distance between any rotor and the center of the quadrotor, b is the thrust factor and d is the drag factor and $\Omega$ is propeller speed.

## 2.3. Quadrotor Morphing and State Space Model

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.

Morphing is a new developmental aspect of unmanned aerial vehicles. This phenomenon is generally associated with aerodynamic and uav structure, so effective control structures should be chosen well in order to be able to control the uav quickly and stably(Barbu, Reginatto, Teel, & Zaccarian, 1999; Jha & Kudva, 2004)

In four-rotor unmanned aerial vehicles, morphing is done by methods such as arm elongation or shortening or by changing the angles between the arm. Morphing can be used as a control element to change the flight dynamics (Prisacariu, Sandru, & Rău, 2011)

This type of morphing is called passive morphing if morphing takes place before the quadrotor takes flight. If Morphing occurs during flight, this type is called active morphing(Oktay & Sal, 2016).

Quadorotor uses active morphing because it performs morphing during flight. Accordingly, the change of arm is shown in the figure below.

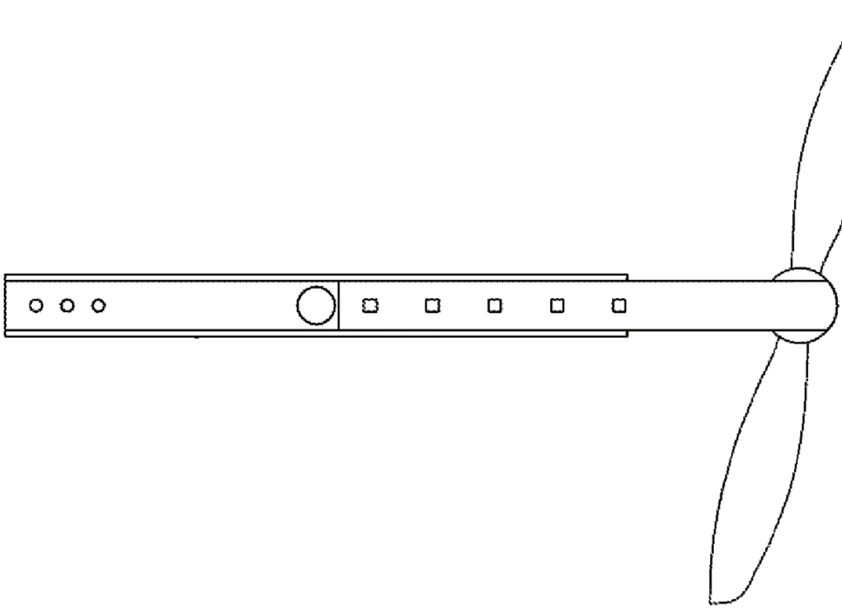

*Figure 5: Notmal Arm Length*

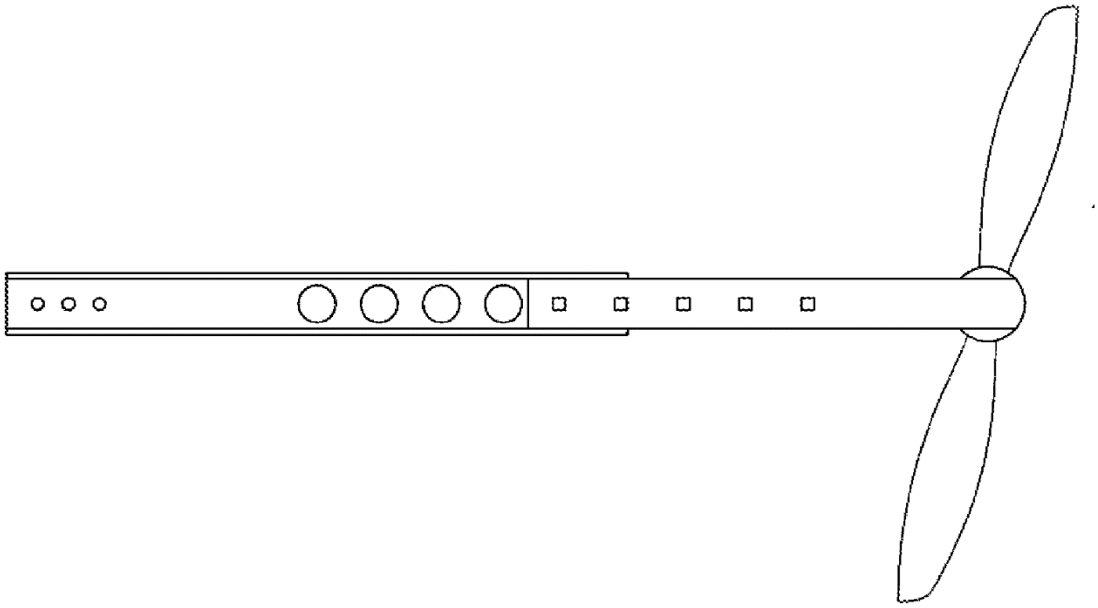

*Figure 6: The extended Arm (10%)*

The state space model is a mathematical model of a physical system expressed by inputs and outputs. In the state space model, the physical system is expressed by first order differential equations. In general, the state space of a linear system is entered in the following form, p input, q output and n state variable.

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

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

Where,

x(t)= State vector,

y(t)= Output vector,

u(t)= Input or control vector,

A= System matrix,

B= Input matrix,

C= Output matrix,

D= Feedforward matrix.

Accordingly, quadrotor longitudinal state space model are as follows:

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

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

Quadrotor longitudinal state space model are as follows:

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

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

### 2.4. Quadrotor Control System

PID algorithm was used for quadrotor control. PID controller is a feedback controller which is widely used in the automotive industry, robotics, aviation and many other areas of the world because of its performance, strong structure and simple. The overall structure of the PID controller is like Figure 7.

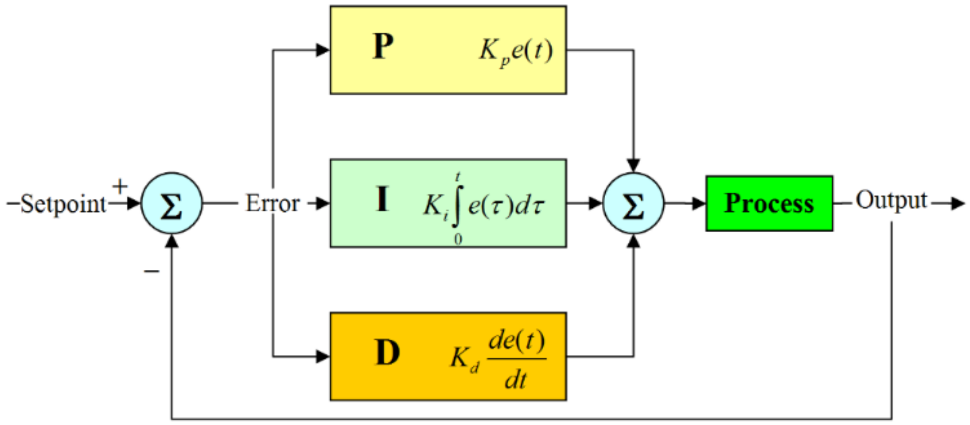


*Figure 7: General structure of PID controller*

PID controller output equation is as follows:

$$u(t) = K_p\, e(t) + K_i\, \int_0^t(t)d(t)\; + K_d\, de(t)/d(t) \tag{5}$$

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 longitudinal and lateral flight:

$$u(t) = K_{p\theta}e(t) + K_{i\theta}\int_0^t e(v)d(v) + K_{d\theta}\frac{de(t)}{d(t)} \tag{6}$$

$$u(t) = K_{p\phi}e(t) + K_{i\phi}\int_0^t e(v)d(v) + K_{d\phi}\frac{de(t)}{d(t)} \tag{7}$$

Accordingly, the quadrotor longitudinal and lateral flight PID block is as follows:

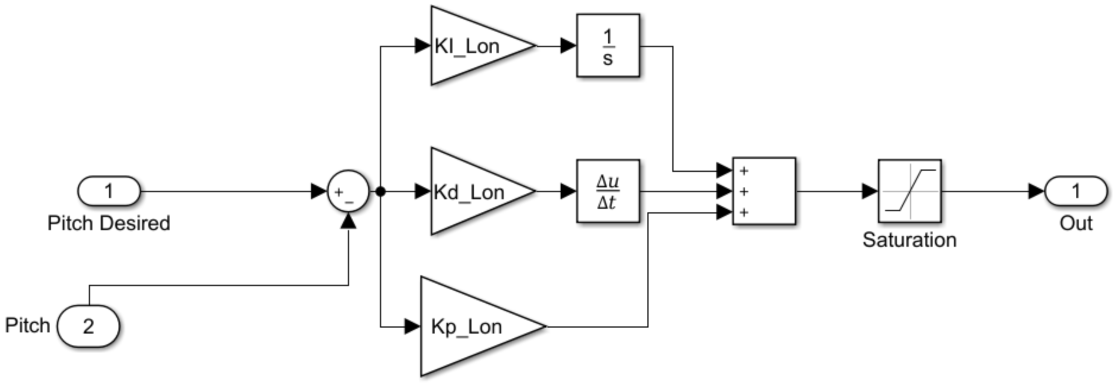


*Figure 8: Longitudinal Flight PID Block*

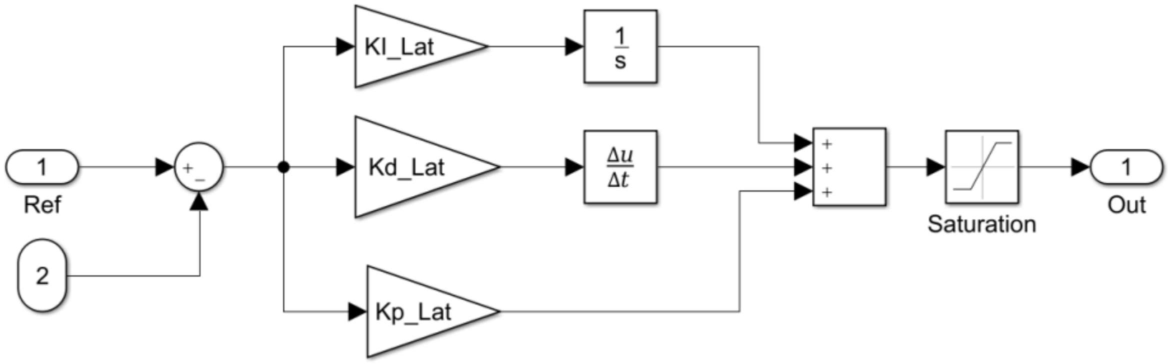


*Figure 9: Lateral Flight PID Block*

## 3. Results and Discussion

Figure 10 shows the case where quadrotor is not morphing. Figure 11 shows the case of morphing.

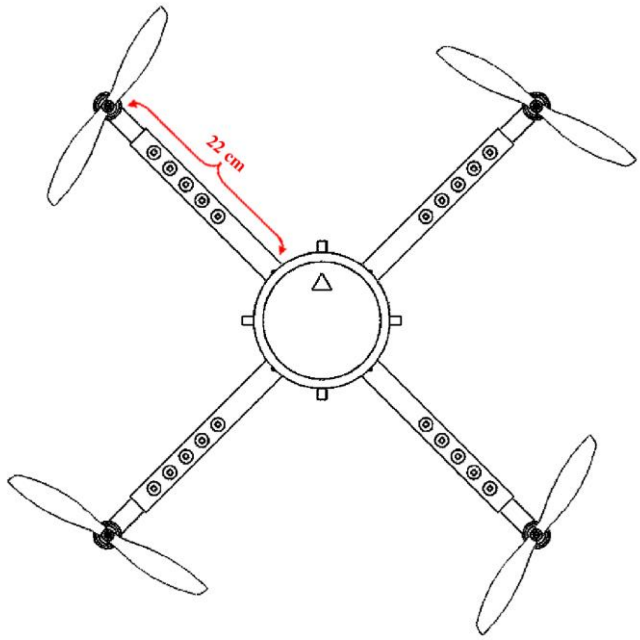


*Figure 10: Without Morphing*

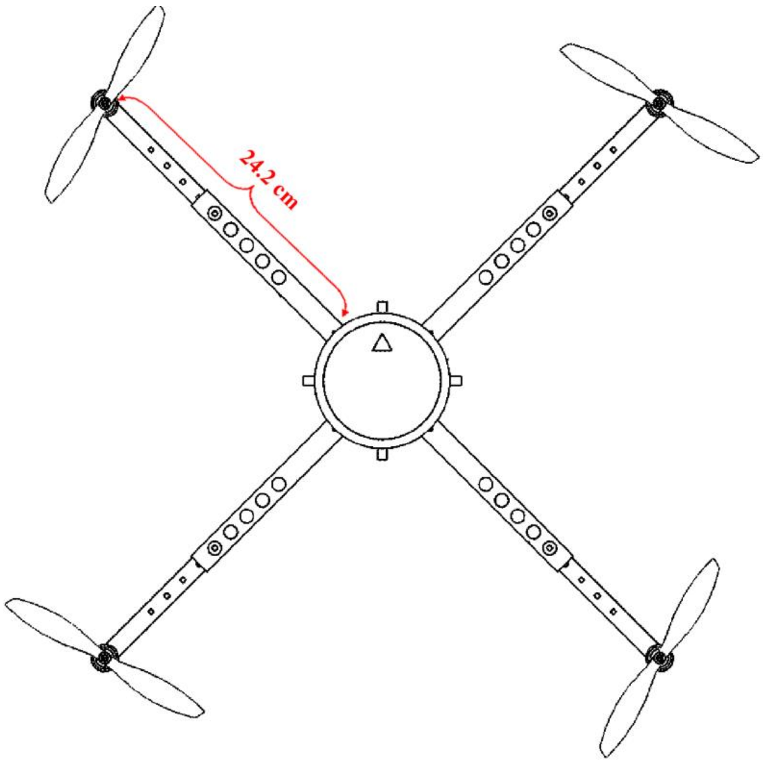


*Figure 11: Quadrotor Morphing*

When morphing occurs in quadrotor, the moment of inertia(I) changes. The reason for this change is the change in arm lengths. If quadrotor L = 22 cm is taken, the mass and inertia moment properties are as in Table 2.

If the length of the arm extended by 10% during the flight ΔL = 2.2 cm is calculated and the arm is extended by 2.2 cm. In this case the new L = 24.2 cm. Accordingly, the new values in Table 3:

*Table 2: Quadrotor Data Without Morphing*

| **QUADROTOR** |
|---|
| $R_{plate}$=6,20 cm |
| $M_{plate}$=20 gr |
| $M_{arm}$=40 gr |
| $M_{motor}$=20 gr |
| $M_{quadrotorr}$=820 gr |
| L=22 cm |
| b=1.0741x$10^{-7}$ |
| d=1.8099x$10^{-9}$ |
| $C_d$=2.6 |
| Ix=0.089 |
| Iy=0.089 |
| Iz=0.0177 |

*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=1.0741x$10^{-7}$ |
| d=1.8099x$10^{-9}$ |
| $C_d$=2.6 |
| Ix=0.091 |
| Iy=0.091 |
| Iz=0.018 |

The pitching PID and turbulence model are given as input to the state space model as in Figure 12.

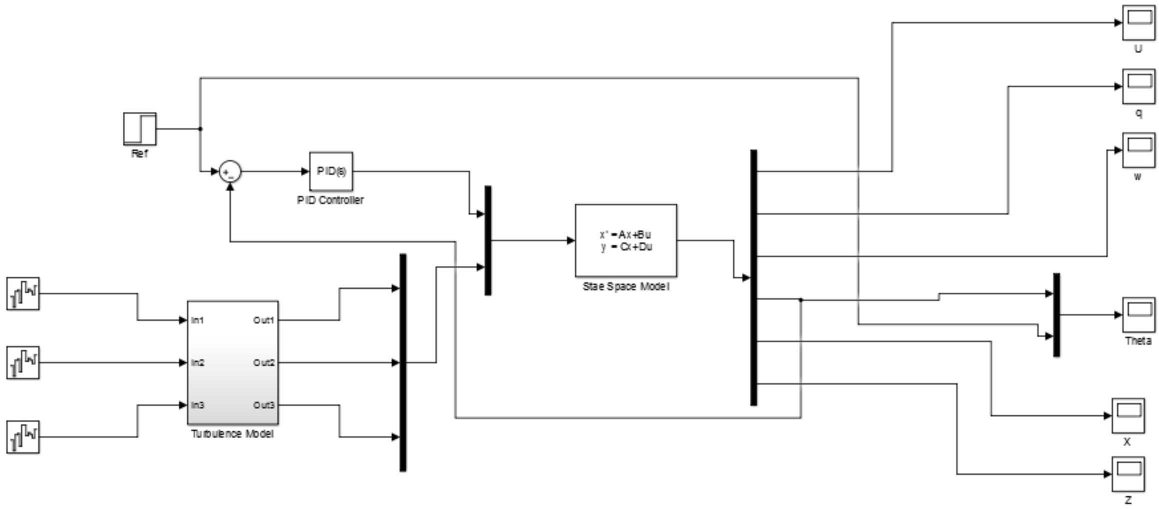


*Figure 12: Longitudinal Flight Simulink Model*

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

*Table 4: Longitudinal Flight PID Coefficient*

| P | I | D |
|---|---|---|
| 50 | 5 | 50 |

Longitudinal flight simulation results are as follows.

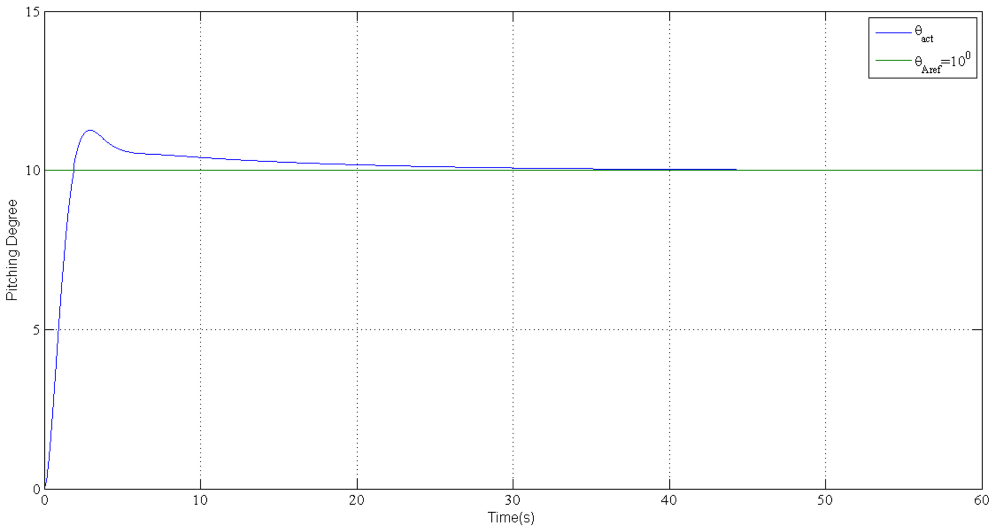


*Figure 13: Longitudinal Flight Simulation Result*

The lateral flight PID and turbulence model are given as input to the state space model as in Figure 14.

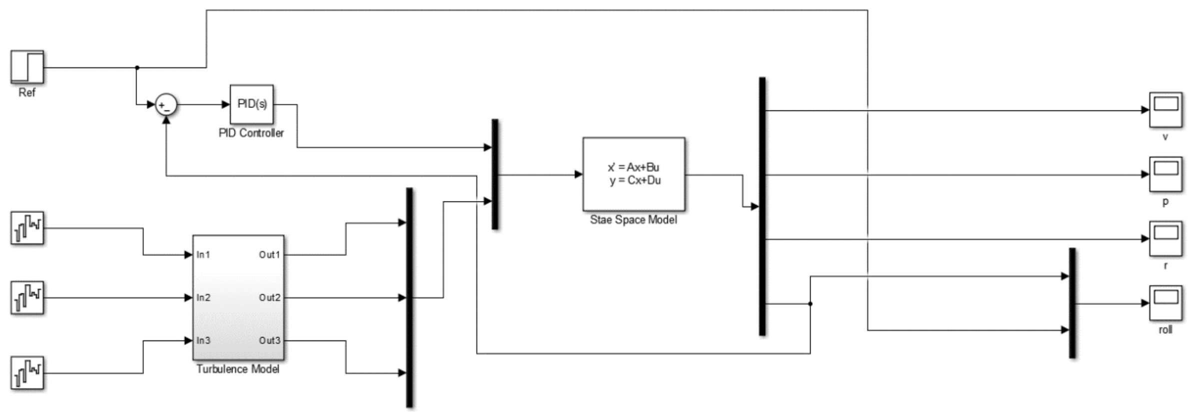


*Figure 14: Lateral Flight Simulink Model*

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

*Table 5: Lateral Flight PID Coefficient*

| P | I | D |
|---|---|---|
| 100 | 100 | 15 |

Lateral flight simulation results are as follows.

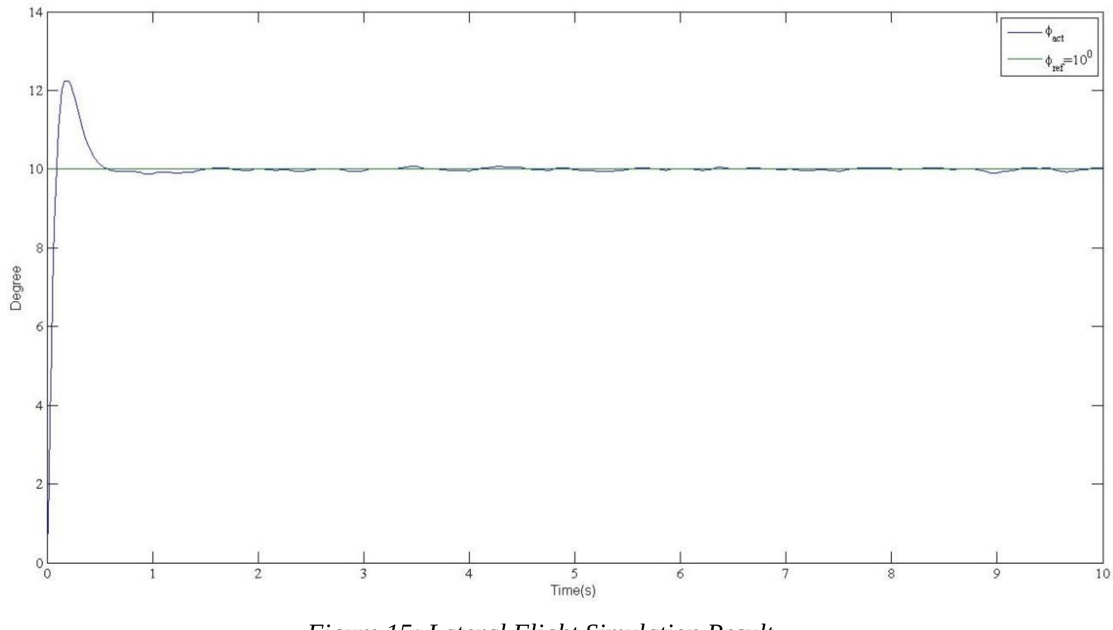


*Figure 15: Lateral Flight Simulation Result*

## 4. Conclusions

In this study, non simultaneous morphing system desings for quadrotors was discussed. Also, the morphing situation during quadrotor longitudinal and lateral 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 does not affect longitudinal flight status. This situation can be seen both from the simulation result and from the following rise time, settling time and overshoot values.

*Table 6: Longitudinal Flight System Characteristic*

| | L=22 cm(No morphing) | L=24.2 cm(%10 morphing) |
|---|---|---|
| Rise Time | 1.26 second | 1.26 second |
| Settling Time | 18.4 second | 18.4 second |
| Overshoot | 12.6 % | 12.6 % |

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

*Table 7: Lateral Flight System Characteristic*

| | L=22 cm(No morphing) | L=24.2 cm(%10 morphing) | L=26.4(%20 morphing) |
|---|---|---|---|
| Rise Time | 0.0631 second | 0.064 second | 0.065 second |
| Settling Time | 0.476 second | 0.479 second | 0.482 second |
| Overshoot | 22.4 % | 22.7 % | 22.9 % |

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.

# 5. References

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