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Research Article

Dynamic Modeling and Simulation of Quadrotor for Different Flight Conditions

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Abstract

In this paper, a four-rotor unmanned aerial vehicle was modeled, a control system was designed and performance evaluations were made. For the control system, a separate mathematical model of the unmanned aerial vehicle longitudinal, lateral and vertical take-off and landing operations is omitted and is expressed as a state space model. The mathematical model of the wind disturbances that will affect the unmanned aerial vehicle during the flight was created and the situation was added to the space model. Proportional Integral Derivative (PID) control algorithm was used as the control. Unmanned aerial vehicle modeling was done in Solidworks and simulations were done in Matlab / Simulink program.

Keywords: Quadcopter, Quadrotor, Unmanned air vehicle, Zankacopter, PID, State space model, Control

1. Introduction

The quadrotor or quadcopter are unmanned aerial vehicles capable of vertical take-off and landing (VTOL). Maneuverability is high. Although control systems are complex, they are structurally simple. It has four rotors and the rotors are positioned equal distance from the quadrotor center of mass. They utilize the forces produced by the rotors and are unmanned aerial vehicles with rotating wing, which form the thrust force by means of propellers. They differ from the standard helicopters in using rotors with fixed-pitch blades. When the quadrotor first came out, the pilots controlled many control parameters and their performance was quite bad. However, thanks to advanced control techniques and advanced high capacity sensors, the pilots have very little workload and their performance has improved considerably.

Quadrotors are structurally simple but uncontrolled aerial vehicles, which are very interesting and have been researched and developed, although the control systems are complex. In recent years, the interest shown on these vehicles has left behind the interest shown to manned aircraft. Quadrotors have many advantages over standard helicopters or manned aircraft. Some of these advantages; low production costs, the ability to add features according to need and eliminate the risk of the pilots in hazardous work environments[1]. In particular, quadrotors have been used in many areas, including hazardous and dangerous areas where people cannot dissolve. In civilian use, quadrotors are being used in areas such as hobby, agriculture, aerial photography and firefighting. In military use, quadrotors are used in many areas such as determination of enemy forces, port and coast security, land search, surveillance, mine screening, long distance and high altitude discoveries, spy communication, determination of radar systems[2]. It has attracted the attention of many researchers due to its success in search and rescue, exploration and security[3, 4].

In F. Solc[5], the unmanned aerial robot quadrotor full control and modeling was working on. His mathematical model was nonlinear and benefited from Newtonian laws of motion. He used the state variables approach in the control system and made the simulations by creating the model.

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In Prabha[6], he studied on X quadrotor modeling and simulation. Its dynamic performance was realized by using PID algorithm which is nonlinear quadrotor control.

In Jun Wang[7], he studied the types of quadrotor attitude when disturbance was applied. In this study, tried to show the difference between Fuzzy Logic Controller and PID Controller. As a result, the Fuzzy Logic controller is faster than the PID controller and showed with graphs.

In G. Ononiw[8], he worked on a quadrotor for payload delivery. In the design, the quadrotor was controlled via wireless from the ground control center. PID was used as the control. The results showed that the quadrotor showed stable attitude with PID control and compensated under disturbance.

In S. C. Quebe [9] explored topics relevant to navigation and control of a small indoor unmanned aerial vehicle. The observer or estimator was designed using an Extended Kalman Filter and estimation quadrotor model parameters using an SIR particle filter.

In Jun and Yuntang [10], they analyzed quadrotor dynamic characteristics and PID controller behavior. The authors designed a controller to adjust the position and orientations of the quadrotor. At the designed PID controller, the system overshoot the small, steady state error approximately zero, the system response was quick and also the result of the increase in quadrotor performance and a strong stabilize.

In [11] A. Alkamachi a trajectory tracking controller was proposed, in which four PID controllers are designed to stabilize the quadrotor and to achieve the required altitude and orientation. However, a nested loop PID controllers are designed to track the desired x and y position of the quadrotor.

Silva[12] has worked on the practical control and model of the unmanned aerial vehicle. He adjusted the angular velocities and yaw rate with the PID algorithm. As a result he has received enough practical results with low cost equipment.

In the study of Jong and Lyou's[13], they applied the PID algorithm for quadrotor hover and tacking. They have also been tested in real time and have determined the stady state error for the hover to be 8 cm at the maximum z-axis and 7 cm at the X and Y axes.

In the study of Abhijit Das etc.[14], they conducted a research on the realization of a quadrotor with the backstepping control algorithm. The quadrotor had a non-linear structure. The quadrotor dynamics were simplified in the helicopter form. As a result, they successfully implemented the backstepping control.

In Yogianandh, Riaan and Glen[15], they conducted a study on the quadrotor dynamic model. They used PD for quadrotor control and simulated matlab / simulink.

In Hossein[16], a quadrotor using the PID controller worked on attitude control. PID tuning used analitic method. Matlab / Simulink made simulations and concluded that the recommended controller provided adequate performance.

Kada [17] designed a control system with robust PID. The system uses the deadbeat response and model reduction techniques to overcome the conventional shortcomings. The test results on the controller showed that a good time domain response is suitable for effective resourcefulness and real time applications in uncertainty situations of the system.

In the study of Praveen and Pillai[18], PID control was applied for quadrotor stabilization. PID parameter gains are selected according to error. In Matlab, they made a prototype of quadrotor and applied PID to it. Quadrotor tests working and performance and obtains the desired outputs.

2. Material and Methods

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

2.1. Quadrotor Description

As shown in Figure 1, the quadrotor has four rotors to produce the propeller powers of f_i = 1,2,3,4. Four rotors are two pairs (1, 3 and 2, 4). One pair rotates clockwise, while the other rotates counter clockwise in order to balance the torques.

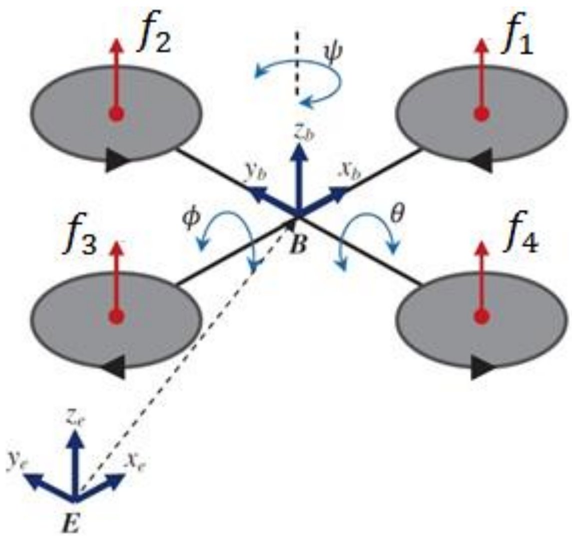


Figure 1: Quadrotor configuration

The yaw movement is obtained from the counter torque between each of the propellers. While each rotor rotates at an equal angular velocities, the net yaw is zero, but the velocities difference between the two pairs creates a positive or negative yaw. Forward or backward motion which is related to the pitch, θ angle can be obtained by increasing the back (front) rotor thrust and decreasing the front (back) rotor thrust. Finally, a sideways motion which is related to the roll, φ angle can be achieved by increasing the left (right) rotor thrust and decreasing the right (left) rotor thrust. Figure 2 shows the various movements of a quadrotor due to changes in rotor speeds.

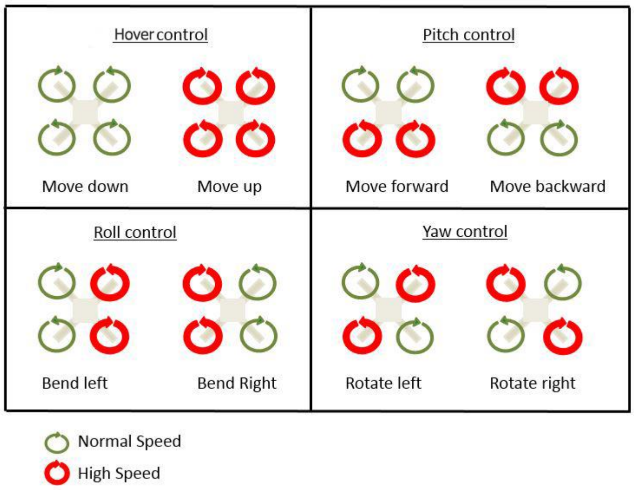


Figure 2: Quadrotor movement

2.2. Quadrotor Kinematic Model

The quadrotor has two coordinate systems, as shown in Figure 1. These:

- Earth Fixed Frame (E)
- Body Fixed Frame (B)

Some quadrotor physical properties are measured in earth fixed frame (roll, pitch and yaw angles, angular velocities), while some properties are measured in body fixed frame (linear accelerations)[19].

The rotation matrix R between earth fixed frame and body fixed frame is obtained by three consecutive rotations roll, pitch and yaw (Euler's angle) about x, y and z axes, respectively.

R rotation matrix is as follows;

$$R = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\psi\sin\theta\cos\psi - \cos\phi\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & \sin\theta\cos\phi\sin\psi - \sin\phi\cos\psi & \cos\theta\cos\phi \end{bmatrix} \quad (1)$$

T is a matrix for angular transformations[20].

$$T = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \frac{\sin(\phi)}{\cos(\theta)} & \frac{\cos(\phi)}{\cos(\theta)} \end{bmatrix} \quad (2)$$

2.3 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[21, 22]:

- 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.

If the velocities of the propellers are expressed by f_i, the total thrust generated by the four propellers is defined by f_i as follows:

$$T = \sum_{i=1}^{4} f_i \tag{3}$$

Where f_i [23].

$$f_i = 4.392399\text{x}10^{-8}.\,\mathrm{RPM}.\frac{\mathrm{d}^{3.5}}{\sqrt{\mathrm{pitch}}}(4.23333\text{x}10^{-4}.\,\mathrm{RPM}.\,\mathrm{pitch} - \mathrm{V_0}) \tag{4}$$

RPM is propeller rotations per minute; pitch is propeller pitch, in inches; d is propeller diameter, in inches; and V0 is the forward airspeed, freestream velocity, or inflow velocity (depending on what you want to call it), in m/s.

The inputs must apply to the system in order to control the behavior of the quadrotor. The torque applied to the device along an axis is the difference between the torques applied by each propeller on the other axes[22]. The values of the input forces and torques proportional to the squared speeds of the rotors[24],

$$\left.\begin{aligned} f_t &= \mathrm{U_1} = \mathrm{b}(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ \tau_x &= \mathrm{U_2} = \mathrm{bl}(-\Omega_1^2 - \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ \tau_y &= \mathrm{U_3} = \mathrm{bl}(\Omega_1^2 - \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \\ \tau_z &= \mathrm{U_4} = \mathrm{d}(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2) \end{aligned}\right\} \tag{5}$$

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 full quadrotor non-linear dynamic model with the x,y,z motions as a consequence of a pitch, roll and rotation is as follows.

$$\left.\begin{aligned}
\dot{x} &= w[\mathrm{s}(\phi)\,\mathrm{c}(\psi) + \mathrm{c}(\phi)\,\mathrm{c}(\psi)\,\mathrm{s}(\theta)] - v[\mathrm{c}(\phi)\,\mathrm{s}(\psi) - \mathrm{c}(\psi)\,\mathrm{s}(\phi)\,\mathrm{s}(\theta) + u[\mathrm{c}(\psi)\,\mathrm{c}(\theta)]] \\
\dot{y} &= v[\mathrm{c}(\phi)\,\mathrm{c}(\psi) + \mathrm{s}(\phi)\,\mathrm{s}(\psi)\,\mathrm{s}(\theta)] - w[\mathrm{c}(\psi)\,\mathrm{s}(\phi) - \mathrm{c}(\phi)\,\mathrm{s}(\psi)\,\mathrm{s}(\theta) + u[\mathrm{c}(\theta)\,\mathrm{s}(\psi)]] \\
\dot{z} &= w[\mathrm{c}(\phi)\,\mathrm{c}(\theta)] - u[\mathrm{s}(\theta)] + v[\mathrm{c}(\theta)\,\mathrm{s}(\phi)] \\
\dot{\phi} &= p + r[\mathrm{c}(\phi)\,\mathrm{t}(\theta)] + q[\mathrm{s}(\phi)\,\mathrm{t}(\theta)] \\
\dot{\theta} &= q[\mathrm{c}(\phi)] - r[\mathrm{s}(\phi)] \\
\dot{\psi} &= r\frac{\mathrm{s}(\phi)}{\mathrm{c}(\theta)} + q\frac{\mathrm{s}(\phi)}{\mathrm{c}(\theta)} \\
\dot{u} &= (vr - wq) + g\,\mathrm{s}(\theta) \qquad \dot{v} = (wp - ur) - g\,\mathrm{c}(\theta)\,\mathrm{s}(\phi) \\
\dot{w} &= (uq - vp) - g\,\mathrm{c}(\theta)\,\mathrm{s}(\phi)\frac{U_1}{m} \\
\dot{p} &= \frac{I_y - I_z}{I_x}qr + \frac{U_2}{I_x} \\
\dot{q} &= \frac{I_z - I_x}{I_y}pr + \frac{U_3}{I_y} \\
\dot{r} &= \frac{I_x - I_y}{I_z}pq + \frac{U_4}{I_z}
\end{aligned}\right\} \tag{6}$$

2.4 State Space Model

Nowadays, it is well known that one of main advantages of the state space method is modelling of multiple-input and multiple-output control system. When the equations of a system under control is highly nonlinear it is necessary to applicate linearization[25]. 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 $\mathrm{x(t)}$ state vector, $\mathrm{u(t)}$ control or input vector, $\mathrm{y(t)}$ output vector, A system vector, B input vector, C output vector and D feed forward vector.

If the non-linear equations given in equation 6 are linearized, the following equations are obtained:

$$\left.\begin{aligned}
\dot{\phi} &= p \\
\dot{\theta} &= q \\
\dot{\psi} &= r \\
\dot{p} &= \frac{\tau_x}{I_x} \\
\dot{q} &= \frac{\tau_y}{I_y} \\
\dot{r} &= \frac{\tau_z}{I_z} \\
\dot{u} &= -g\theta \\
\dot{v} &= g\phi \\
\dot{w} &= \frac{f_t}{m} \\
\dot{x} &= u \\
\dot{y} &= v \\
\dot{z} &= w
\end{aligned}\right\} \tag{7}$$

$[\mathrm{x} \quad \mathrm{y} \quad \mathrm{z} \quad \phi \quad \theta \quad \psi]^{\mathrm{T}}$ the vector containing the linear and angular position of the quadrotor in the earth frame and $[\mathrm{u} \quad \mathrm{v} \quad \mathrm{w} \quad \mathrm{p} \quad \mathrm{q} \quad \mathrm{r}]^{\mathrm{T}}$ the vector containing the linear and angular velocities in the body frame[26]. u input or control vector: $\mathrm{u} = [f_{\mathrm{t}} \quad \tau_{\mathrm{x}} \quad \tau_{\mathrm{y}} \quad \tau_{\mathrm{z}}]^{\mathrm{T}}$

After the linearization is done and the input matrix is determined, the equation 7 is divided into two parts. The first part represents the longitudinal flight $\mathrm{x},\ \mathrm{z},\ \mathrm{u},\ \mathrm{w}, \mathrm{q}, \theta$ and the second part is the $\mathrm{y},\ \mathrm{v},\ \mathrm{p},\ \mathrm{r},\ \phi$ and ψ values representing the lateral flight. Accordingly, for the longitudinal and lateral flight state space models are as follows.

Longitudinal flight state space model:

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

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

Lateral flight state space model:

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

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

2.5 Control System

PID is a control mechanism used in common industrial control systems. It is also widely used in quadrotor control. A PID controller calculates the difference between a set point and a desired set point in the process as an "error" value. The controller tries to reach the set point by downloading the minimum value of the error.

The control output is passed through three separate mathematical operations and is obtained by summing. System effects are as follows.

Proportional Effect (P): Effective as the output multiplied by a certain "gain" value of the error. Calculates the current error.

Integral Effect (I): The effect of the control is proportional to the sum of all the errors in the moment up to the moment the effect is calculated. In other words, the integral effect means the sum of errors the system has made in the past.

Derivative Effect (D): It has a proportional effect on the output of the system, according to the change of the error. So it calculates the prediction of the future error.

75% of the applications in the industry have PID applied. Karl Arstom defines this algorithm which has a wide application area as follows:

$$u(t)=K_p e(t)+K_i\int_0^t e(v)d(v)+K_d\frac{de(t)}{d(t)} \qquad (8)$$

Where, K_p proportional coefficient, K_i integral coefficient and K_d is the derivative coefficient.

If a traditional PID structure is represented by blocks, it is as follows:

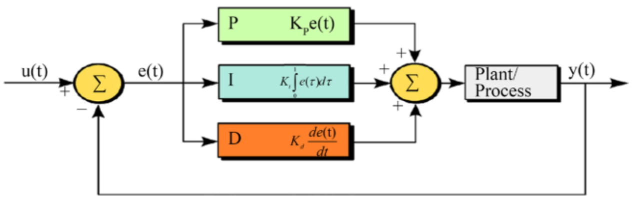


Figure 3: Traditional PID controller

Accordingly quadrotor hover, longitudinal and lateral flight PID would be as follows, respectively:

$$u(t)=K_{ph}e(t)+K_{ih}\int_0^t e(v)d(v)+K_{dh}\frac{de(t)}{d(t)} \qquad (9)$$

$$u(t)=K_{p\theta}e(t)+K_{i\theta}\int_0^t e(v)d(v)+K_{d\theta}\frac{de(t)}{d(t)} \qquad (10)$$

$$u(t) = K_{p\phi} e(t) + K_{i\phi} \int_0^t e(v)d(v) + K_{d\phi} \frac{de(t)}{d(t)} \qquad (11)$$

where K_{ph} , K_{ih} , K_{dh} hover PID coefficients, respectively. $K_{p\theta}$, $K_{i\theta}$, $K_{d\theta}$ longitudinal flight PID coefficients, respectively. $K_{p\phi}$, $K_{i\phi}$, $K_{d\phi}$ lateral flight PID coefficients, respectively.

UAVs missions in real–life applications encounter significant disturbances generated by atmospheric turbulence, which is a complex physical phenomenon and is typically modeled using elements from stochastic fluid theory. Therefore, it is preferable to pass a white noise through a forming filter in order to generate a proper wind-gust model. In literature, two main forming filters can be found: the Dryden and the von Karman. It is von Karman approach that is utilized in this paper[27].

According to Von Karman model, longitudinal and lateral state space models are as follows.

Longitudinal flight state space model[28]:

$$\dot{x} = Ax + B_{\eta} + C_{\xi}$$

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_0 & 0 \\ M_u & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta\theta \end{bmatrix} + \begin{bmatrix} X_\delta & X_{\delta_T} \\ Z_\delta & Z_{\delta_T} \\ M_\delta & M_{\delta_T} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta_{\delta_e} \\ \Delta_{\delta_T} \end{bmatrix} + \begin{bmatrix} -X_u & -X_w & 0 \\ -Z_u & -Z_w & 0 \\ \_M_u & -M_w & -M_q \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_g \\ w_g \\ q_g \end{bmatrix}$$

Lateral flight state space model[29]:

$$\dot{x} = Ax + B_{\eta} + C_{\xi}$$

$$\begin{bmatrix} \Delta\dot{v} \\ \Delta\dot{p} \\ \Delta\dot{r} \\ \Delta\dot{\phi} \end{bmatrix} = \begin{bmatrix} Y_v & Y_p & -(u_0 - Y_r) & -g\cos(\theta_0) \\ L_w^* + \frac{I_{xz}}{I_x} N_v^* & L_p^* + \frac{I_{xz}}{I_x} N_p^* & L_r^* + \frac{I_{xz}}{I_x} N_r^* & 0 \\ N_v^* + \frac{I_{xz}}{I_z} L_v^* & N_p^* + \frac{I_{xz}}{I_z} L_p^* & N_r^* + \frac{I_{xz}}{I_z} L_r^* & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta v \\ \Delta p \\ \Delta r \\ \Delta\phi \end{bmatrix} + \begin{bmatrix} X_\delta & X_{\delta_T} \\ Z_\delta & Z_{\delta_T} \\ M_\delta & M_{\delta_T} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta_{\delta_e} \\ \Delta_{\delta_T} \end{bmatrix} + \begin{bmatrix} -X_u & -X_w & 0 \\ -Z_u & -Z_w & 0 \\ \_M_u & -M_w & -M_q \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_g \\ w_g \\ q_g \end{bmatrix}$$

3. Results and Discussion

The top and side view of the quadrotor according to the model drawn in Solidworks are as follows.

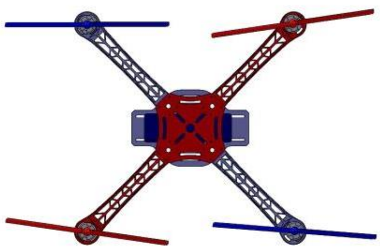


Figure 4: Quadrotor top view

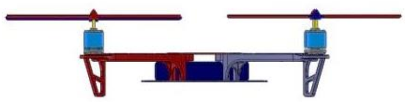


Figure 5: Quadrotor side view

The parameters of quadrotor obtained from the drawn model are given in the table below.

Table 1: Quadrotor data

QUADROTOR
$Ix=28.8x10^{-3}$
$Iy=28.8x10^{-3}$
$Iz=26x10^{-3}$
m=0.82
l=0.22
$b=1.0741x10^{-7}$
$d=1.8099x10^{-9}$

Depending on the model and parameters quadrotor hover, longitudinal and lateral flight simulink models are as follows, respectively.

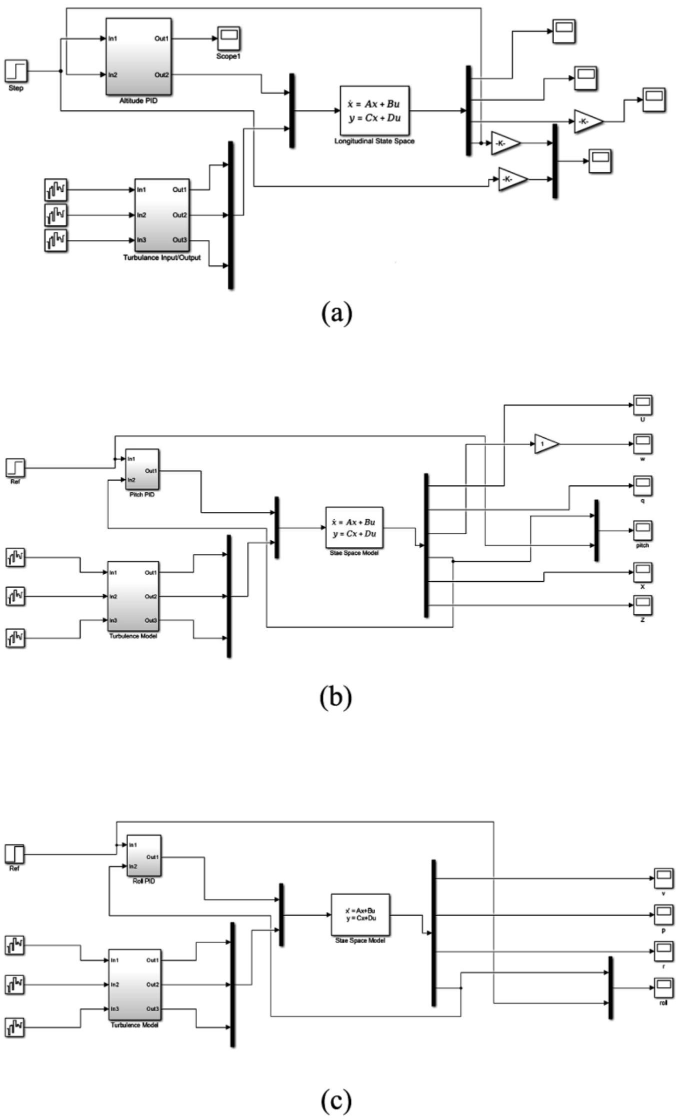


Figure 6: Simulink model (a) Hover flight (b) Longitudinal flight (c) Lateral flight[30-32]

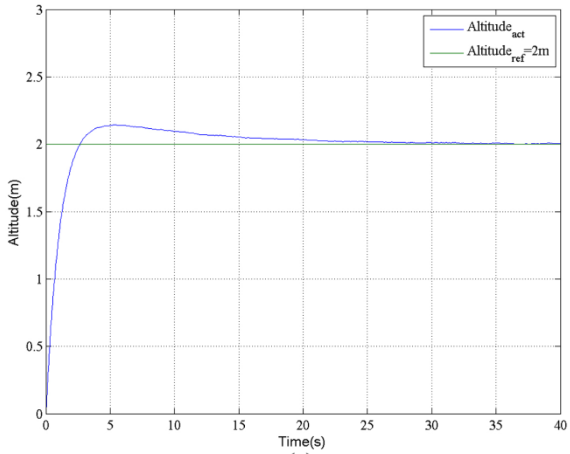
The state space models created for each flight mode were entered into the state space model in the simulink separately. In addition, to test that quadrotor works in a disturbances environment, the Von Karman Model has been added to the simulation.

The PID block coefficients generated for the simulation are listed in the following table.

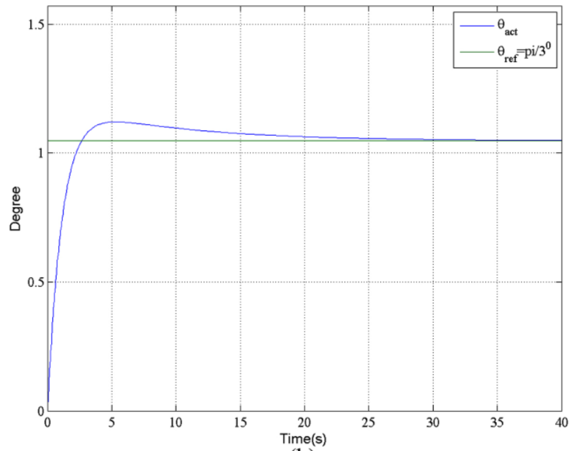
Table 2: PID coefficient

	Hover Flight	Longitudinal Flight	Lateral Flight
P	50	50	100
I	5	5	100
D	50	50	15

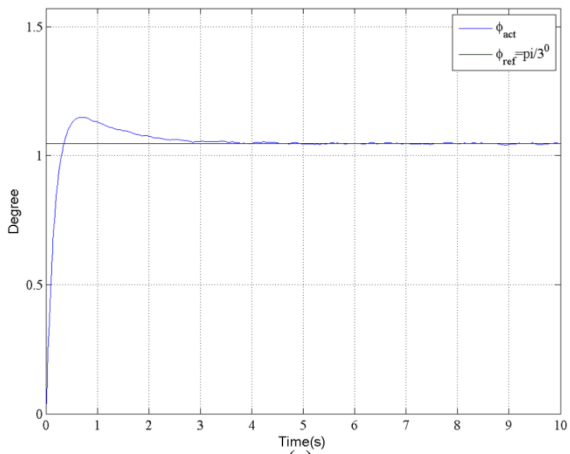
The following graphs are obtained for each flight mode according to the simulation results.



(a)



(b)



(c)

Figure 7: Simulation results (a) Hover flight (b) Longitudinal flight (c) Lateral flight

4. Conclusions

In this study, longitudinal, lateral and hover flight of quadrotor is discussed. Quadrotor model was created in Solidworks program and data obtained from it was made with Simulink model.

The PID algorithm was used to control the quadrotor. The von Karman turbulence model was used for the turbulence model. The controller that we suggested showed during the longitudinal, lateral and hover flight that the quadrotor we developed has successfully controlled the dynamic models in both noise and noiseless environment.

During longitudinal, lateral and hover flight, rise time, overshoot, settling time, steady state error which is criteria for design performances were obtained within satisfactory borders.

During longitudinal, lateral and hover flight, demanded circle was controlled successfully.

During longitudinal, lateral and hover flight, satiation function on the control surface obeyed successfully.

During longitudinal, lateral and hover flight, other state variables did not demonstrate catastrophic behavior.

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