CHAPTER

1 INTRODUCTION

Figure 1-1Quadrotor UAV

1.1 INTRODUCTION

An unmanned aerial vehicle (UAV) is an unpiloted aircraft which can either be controlled from any remote location or a preprogrammed flight plan is used to fly it. Most of the helicopters of this generation are unmanned. They are very useful in military and civil applications. Some of them are

- Accomplishing tasks into dangerous situations where human life is in danger.
- Agriculture.
- Following a target.
- Scouting.
- Rescue.
- Surveillance.

1.2 HISTORY

It is always dream of man to fly, boosting him to work on every possible way to realize this dream. Mankind's wish for flying has been obviously expressed throughout his history. It took the form of legends, myths as the spaceship vision in the book of Ezekiel (Bible) or the flying chair of Prophet Solomon (Peace Be Upon Him) [1]. It was the biggest challenge for human being that has generated centuries of frustration and hundreds of dramatic attempts without ever fading [2].

Discovery of kite was first successful attempt of flying from Chinese in 400BC that made humans to think about flying. Ancient Alexandrian engineer Hero created a machine aeolipile based on the principles of fluidics and pressure which used jets of steam to create rotary motion.

In 1490 Leonardo DaVinci gave the idea of flight by drawing more than 100 drawings including a design for a machine that could be described as an "aerial screw", that any recorded advancement was made towards vertical flight. In 1754 a spring powered rotor was demonstrated by Mikhail Lomonosov. Some more contribution was given by Christian de Launoy in 1783 and Sir George Cayley in 1784. Alphonse Pénaud developed co-axial rotor in 1870. The word helicopter is derived from two Greek words Helix and Pteron, screw and wing was used by Ponton d'Amécourt first time in 1863. He demonstrated a steam powered modeled using newly invented material Aluminum.

In 1877 Forlanini demonstrated an unmanned steam powered model able to fly 20 seconds at 12 meters after vertical takeoff. The first electrical model was built in 1887. In 1907, between 14 August and 29 September two French brothers, Jacques and Louis Breguet demonstrated the Gyroplane No.1. Although there is some uncertainty about the dates, sometime between 14 August and 29 September 1907, its flight was 0.6 m for 1 Minute. This flight is not considered as first free flight as it was unsteady. The first free and controlled flight was achieved on 13 Nov 1907 by French inventor Paul Cornu who designed and built a Cornu helicopter that used two 20-feet (6 m) counter-rotating rotors driven by a 24-hp (18-kW) [5]. Its flight was 1 foot for 20 sec. Later it achieved a height of 6.5 m but proved to be unstable. In 1922, Georges de Bothezat built first helicopter in which the propeller was located at each end of the x-shaped structure [6].

1.3 QUADROTOR UAV

Quadrotor UAV or more precisely Quadrotor VTOL (Vertically Take OFF and Landing) UAV consists of 4 rotors. Two of them rotate in clockwise and other two in counter clockwise direction. It is controlled by varying the speed of anyone or all. Sometimes it is referred as under-actuated system because it has only four inputs to control the six degrees-of-freedom. Two degrees-of-freedom are coupled in the sense that the translational position depends on the orientation of the aircraft.

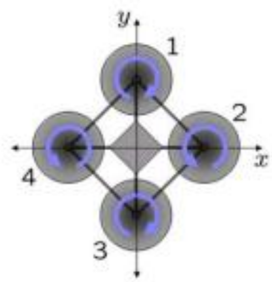

Figure 1-2 Direction of four rotors of Quadrotor UAV

When four rotors are rotating at same speed then an upward thrust is produced to lift the Quadrotor. If this thrust just balances the gravity then UAV hovers. As pair of rotors spin in opposite direction, Clockwise torque of motors 1 and 3 balances counterclockwise torque produced by rotation of motors 2 and 4. As a result yaw angle remains constant. An increase in the speed of motor 1 and decrease in the speed of motor 3 causes a non-zero pitch angle. Similarly roll angle can be adjusted by varying the speeds of motors 2 and 4. Following figure summarizes above discussion.

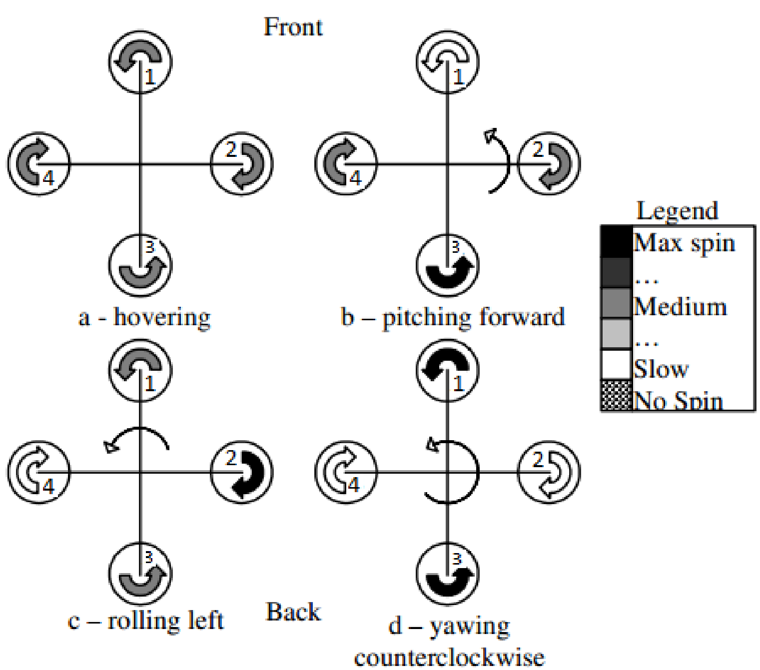

Figure 1-3 Variation in positions of UAV by Applying torque

1.4 ADVANTAGES OF THE QUADROTOR UAV

Despite the requirement of a very complex system for controlling the Quadrotor UAV it has numerous advantages over other designs. Some of them are given below.

1.4.1 LESS VOLUME

Use of four rotors in this UAV allows having smaller and lighter rotors in comparison of mono rotor UAV. Hence quadrotor occupy less space. This gives an advantage when UAV is used in indoor environments. For example, in the undesired case of a blade striking an object, small diameter of rotor will produce very less damage relatively. This makes it suitable for close interaction.

1.4.2 SIMPLE MECHANICAL DESIGN

There is no need of mechanical linkage to vary pitch angle, which makes the structure and maintenance simple.

1.4.3 LOW POWER COST

As the rotors are smaller than that of other types, they use less amount of kinetic energy.

1.4.4 HOVERING AND LOW SPEED FLIGHT

Stationary position and low speed flight is also possible in Quadrotor UAVs.

1.4.5 GYROSCOPIC EFFECTS

Two rotors rotate in clockwise and other two in counter clockwise direction. This movement is very effective in eliminating gyroscopic effect that occurs in helicopters.

1.5 DISADVANTAGE

Being inherently unstable vehicle it requires complex and costly control system to control.

1.6 APPLICATIONS

In section 1.5 it has already been discussed that Quadrotor UAV has many advantages over other designs. Due to these advantages it has become very popular in civil and military applications. They are very suitable solution to work in any hazardous environment. In agriculture they are used for irrigation purpose. They are also used in scouting, surveillance and rescue applications. In military applications it is used in Drones bombardment and to have a look beyond the horizon.

It is also serving as a teaching aid for students of control theory. They change control algorithm and check the effect of these changes.

1.7 FUNDAMENTAL ISSUES

Quadrotor UAV is an inherently unstable vehicle. Moreover it faces many disturbances during flight operation. These disturbances include aero dynamical disturbances, external disturbances, sensor measurement noise, some un-modeled dynamics parameter variations such as mass and inertia. These control challenges have attracted many researchers and many solutions have been proposed. It is very difficult to design a controller that can address all problems. Many control schemes are available each of them provide solution to some problems.

1.8 CURRENT RESEARCH

In this section current trend of research in this field will be presented. Many researchers have designed controller to solve stabilization problems of UAV. These designs range from very basic PID and LQR controller to adaptive control methods. PID controllers are less efficient especially for nonlinear control systems. However PID with auto tuning features is used effectively.

Some nonlinear techniques like feedback linearization, sliding mode control, feedback linearization and backstepping controls are also used. Feedback linearization has a serious drawback of cancelling all nonlinearities whether they are useful or not.

To address the problem of uncertainty and disturbance adaptive controllers such as adaptive backstepping and adaptive sliding mode controllers are used. These controllers provide very good steady state response. H_∞ feedback controllers are also used in this field to provide robustness.

Concept of intelligent controllers is also being used now a days. Neural networks use a learning scheme to identify the system and produce an adaptive control to reject all disturbances. Fuzzy logic uses a very effective concept of fuzziness and rule based to provide excellent result in this field.

A lot of research work has been done in the field of quadrotor modeling and control. Obviously it is impossible to present all the work. In the next chapter a selected part of research will be presented.

CHAPTER

2 LITERATURE SURVEY

It is said that “to gain something you need to lose something”, everything which have some comfort comes with a price. Every control scheme faces many problems such as disturbance, uncertainty, instability, nonlinear behavior etc. Several researchers have addressed nature of these problems and their possible solutions. This chapter presents a brief summary concerning these problems.

2.1 INTRODUCTION

This chapter covers the review of the work done in the field of quadrotor control. It is impossible to present all research work. A brief discussion of research in few selected papers will be given. The next section presents review of previous work done in the field of quadrotor control.

2.2 REVIEW OF PREVIOUS WORK

Recent availability of miniaturized Micro electromechanical motion sensors (MEMS), high power to weight ratio batteries, high speed brushless dc motors and very efficient control techniques make Quadrotor (QR) very attractive for researchers. In past few years there are many projects and studies related to QR using different materials and control techniques. Some of them are given below.

2.2.1 European Aeronautic Defense and Space Company

Quattrocopter (Figure 2-1) was built at European Aeronautic Defense and Space Company. It is a 65 cm electrically powered VTOL and its flight time is only 20 min and flight range of 1Km. Its weight is 0.5 kg. Six MEMS inertial measurement units (IMU) are used for six degree of freedom. One GPS unit and air data sensors (gas sensors) are also used. Total mass of measurement unit is 65 grams, consumes less than three watts at 5 V. The motors are detachable so that the system can be stored in a small space [7].

Fig 2-1: Quattrocopter

2.2.2 Pennsylvania State University

In Pennsylvania State University two different studies had been done on quadrotors [8] and [9]. First was a master thesis that had been done about a quadrotor test bench. PI controller was used to control altitude. Controller was simulated using SIMULINK to show the performance of controller.

Second work done in University of Pennsylvania utilizes Dragon-Flyer as a test-bed. Image processing was used to control the quadrotor dynamics. The controller obtained the relative positions and velocities from the cameras only.

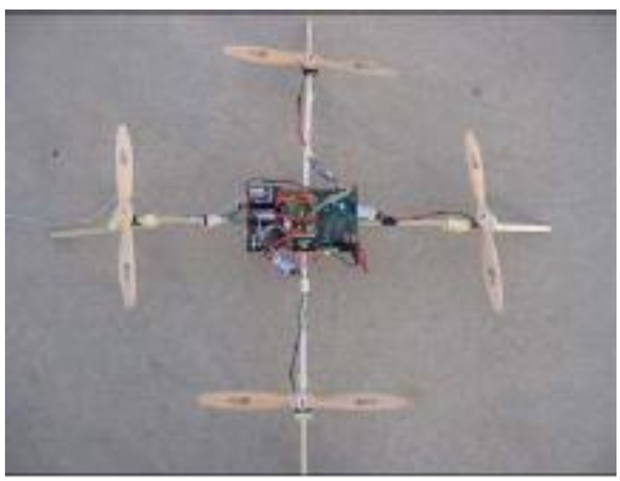

Fig 2-2: Quadrotor designed in Pennsylvania State University

2.2.3 University of British Columbia Vancouver, BC, Canada

In University of British Columbia an H_∞ loop shaping controller was designed to control nonlinear model. Flying mill, DSP system, microprocessor and wireless transmitters were used in experimental setup.

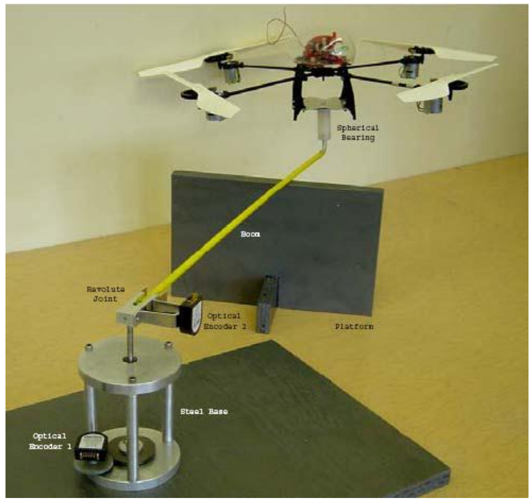

Fig 2-3: Quadrotor developed University of British Columbia Vancouver, BC, Canada

2.3 Applied Control Systems

Several control strategies have been used in literature so far. Some of them are discussed here. Optimal Linear Quadratic regulator (LQR) is used in [10] and [11]. In [12] and [13] Lyapunov stability theory is used that guarantees asymptotic stability. In [5] and [14] back stepping and sliding mode techniques are applied. In [16] feedback linearization and backstepping based PID control technique is utilized to stabilize the quadrotor aerial robot. In [15] dynamic inversion technique is implemented. Robust feedback controllers based on $H\infty$ techniques in [17],

In [18] a trajectory tracking control is proposed. First of all a model of quadrotor is derived based on some assumptions that it is a rigid body and we can derive its model using Newton-Euler formula, As aerodynamic forces and moments are very complicated to model so it is assumed that these effects can be ignored at low speed. Third assumption is taken that plant is symmetric with respect to all three axes. A relationship between the attitude and the linear acceleration is built based on the position error PD closed-loop equation of the quadrotor and a command filtered backstepping control design algorithm is proposed. Control algorithm is applied to the Simulink model and results are obtained.

In [19] output feedback control of a Quadrotor UAV using neural network is proposed. In this paper no assumption is taken for the modeling of UAV but online modeling identification is used to include all uncertainties and nonlinear terms. Only altitude of vehicle is directly measured where all other things were estimated using NN (Neural Network) observer. At the end simulations were performed on MATLAB. Some additional disturbances were added in simulation. A PID controller was also applied to the same model. Comparison shows that on the average 5 times more torque is required in PID controller as compared to NN controller. It is shown using Lyapunov technique that all estimation errors are semi globally uniformly ultimately bounded (SGUUB).

In [20] first of all a PID controller and LQ controllers were designed. Designed controllers were then applied to test bench OS-4. It was concluded that PID controller gives better flight performance in some small perturbations. At the end it was concluded that LQ controller should give better results after improvements.

In [21] adaptive robust controller for stabilization of Quadrotor UAV carrying unknown payload is presented. But no scheme was presented to control angular motion.

In [22] a robust controller is proposed for tracking desired trajectories of a Quadrotor UAV in presence of aerodynamic disturbances. A disturbance observer is used to design a robust controller which estimates the total disturbance acting on the system and provides a control signal to compensate it.

2.4 CONCLUSION

In this chapter many control techniques to control quadrotor have been discussed. Also lot of research has been carried out in achieving stability of Quadrotor UAV as they encounter issues related to aerodynamic disturbances and parameter variation. Next chapter shall present the discussion of designed controller and its specifications.

CHAPTER

3 MATHEMATICAL MODEL

A mathematical model is actually a set of equations which describe the system behavior. Usually dynamic systems are represented by differential equations. Mathematical modeling is not limited with physical sciences but also applicable to the fields of biological sciences and social sciences. Generally it is impossible to develop a precise model of system because some phenomenon cannot be modeled. This leads to some modeling errors but this model is very useful if it describes system dynamics. Mathematical model is very useful to understand the dynamics of system and designing of controller.

3.1 INTRODUCTION

This chapter presents system description and mathematical model of Quadrotor UAV. Section 3.2 covers system description and a mathematical model is derived using Newton Euler's method.

3.2 SYSTEM DESCRIPTION

As it is discussed in introduction that Quadrotor has four rotors and its dynamics depends on the speed of these rotors. Figure 3-1 shows the schematic diagram of QR.

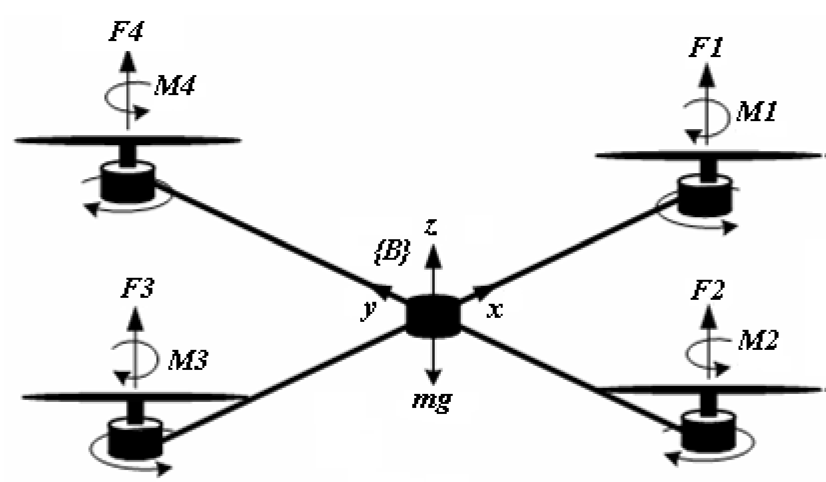

Figure 3-1 Structure of QR UAV

In the figure $M_i,\ i = 1, 2, 3, 4$ represents motor.

Let's define system parameters. m is mass of system. F_i is the force generated by i^{th} motor. I_x, I_y and I_z represent rotational inertia along *x*-axis, *y*-axis and *z*-axis respectively. K_{fax}, K_{fay} and K_{faz} are aerodynamic friction coefficients. Drag coefficient is represented by K_d and d represents the distance between propeller and center of mass of QR UAV. K_p is lift coefficient of rotor that relates the angular speed and force by relation $F_i = K_p\, \omega_i^2$. K_{ftx}, K_{fty} and $K_{ftz}$are translational drag force coefficients.

Table 3-1 describes the values of all real parameters of QR UAV used in [23] and these values will also be used for designing and simulations in this thesis.

Table 3-1 Numerical values for system parameters

K_p	2.9842×10^{-5} N.m / rad / s
K_d	3.232×10^{-7} N.m / rad / s
m	486g
d	25cm
K_{fax}	5.567×10^{-4} N / rad / s
K_{fay}	5.567×10^{-4} N / rad / s
K_{faz}	6.354×10^{-4} N / rad / s
K_{ftx}	5.567×10^{-4} N / m / s
K_{fty}	5.567×10^{-4} N / m / s
K_{ftz}	6.354×10^{-4} N / m / s
J_r	2.8385×10^{-5} N.m / rad / s^2
I_x	3.8278×10^{-3} N.m / rad / s^2
I_y	3.8288×10^{-3} N.m / rad / s^2
I_z	7.6566×10^{-3} N.m / rad / s^2

3.3 MATHEMATICAL MODELING

In this section mechanics principles will be used to develop a mathematical model of QR UAV. Some assumptions are made here to simplify modeling process.

1. QR has symmetrical and rigid structure.
2. Centre of mass coincides with geometrical center.
3. All rotors are totally rigid.
4. Forces of thrust and drag are directly related to the square of rotor speeds.
5. All rotors are independent of each other.

Let E represent an inertial frame of reference as shown in Fig 3-2 and B is a frame of reference rigidly attached with QR as Fig 3-1 exhibits.

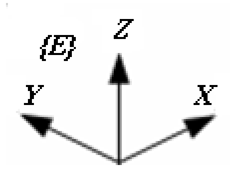

Fig 3-2 Inertial frame of reference

Using the Newton-Euler formalism dynamic equations of system can be written as

$$\dot{\varsigma} \quad = \nu \tag{3-1}$$

$$m\ddot{\varsigma} = F_r + F_t + F_g \tag{3-2}$$

$$\dot{R} \quad = RS(\Omega) \tag{3-3}$$

$$J\dot{\Omega} \ = -\Omega \wedge J\Omega + T_f - T_a - T_g \tag{3-4}$$

Here ς is the position of center of mass in inertial frame E. $J = diag\,(Ix, Iy, Iz)$ is inertia matrix with respect to frame B. Ω denotes angular velocity matrix in inertial frame.

$$\Omega = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta\sin\phi \\ 0 & -\sin\phi & \cos\phi\ cos\theta \end{bmatrix} . \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{3-5}$$

Here $[\phi, \theta\ and\ \psi]$ are Euler angles. For angular motion of very small amplitude Ω can be taken as $[\dot{\phi} \quad \dot{\theta} \quad \dot{\psi}]^T$.

R is transformation matrix as given in [24].

$$R = \begin{bmatrix} Cos\theta\ Cos\psi & Cos\psi\ Sin\theta\ Sin\phi - Sin\psi Cos\phi & Cos\phi\ Sin\theta\ Cos\psi + Sin\phi\ Sin\psi \\ Sin\psi\ Cos\theta & Sin\psi\ Sin\theta\ Sin\phi + Cos\psi\ Cos\phi & Sin\psi\ Cos\phi Sin\theta\ - Cos\psi\ Sin\phi \\ -Sin\theta & Cos\theta & Cos\phi Cos\theta \end{bmatrix} \tag{3-6}$$

Here $S(\Omega)$ is skew-symmetric matrix and defined as

$$S(\Omega) = \begin{bmatrix} 0 & -\Omega_3 & \Omega_2 \\ \Omega_3 & 0 & -\Omega_1 \\ -\Omega_2 & \Omega_1 & 0 \end{bmatrix} \ \forall\, \Omega = [\Omega_1 \quad \Omega_2 \quad \Omega_3]^T \tag{3-7}$$

F_r denotes resultant of forces acted by rotors and given by

$$F_r = \begin{bmatrix} Cos\phi\ Cos\psi\ Sin\theta + Sin\phi\ Sin\psi \\ Cos\phi Sin\theta Sin\psi - Cos\psi in\phi \\ Cos\phi\ Cos\theta \end{bmatrix} . \textstyle\sum_{i=1}^{4} F_i \tag{3-8}$$

F_t is matrix of drag forces and defined as

$$F_t = Diag[-K_{ftx} \quad -K_{fty} \quad -K_{ftz}]\dot{\varsigma} \tag{3-9}$$

F_g is force vector due to gravity.

$$F_g = [0 \quad 0 \quad -mg]^T \tag{3-10}$$

T_f is matrix of torque produced by all rotors in along *x*, *y*, and *z* axes with respect to frame B. and given by

$$T_f = \begin{bmatrix} d(F_3 - F_1) \\ d(F_4 - F_2) \\ K_1(F_1 - F_2 + F_3 - F_4) \end{bmatrix} \tag{3-11}$$

Here $K_1 = K_d/K_p$.

Matrix of resultant of aerodynamic friction torques is given by

$$T_a = Diag[-K_{fax} \quad -K_{fay} \quad -K_{faz}].[{\Omega_1}^2 \quad {\Omega_2}^2 \quad {\Omega_3}^2]^T \tag{3-12}$$

Torque due to gyroscopic effects is given by

$$T_g = \Omega \wedge J_r \begin{bmatrix} 0 \\ 0 \\ \omega_1 - \omega_2 + \omega_{31} - \omega_4 \end{bmatrix} \tag{3-13}$$

Using Equations (3-5) to (3-13) in (3-1) to (3-4) mathematical model of QR UAV is obtained as

$$\begin{aligned}
\ddot{\phi} &= \frac{1}{I_x}\left\{\dot{\theta}\dot{\psi}\left(I_y - I_z\right) - K_{fax}\dot{\phi}^2 - J_r\varpi\dot{\theta} + dU_2\right\} \\
\ddot{\theta} &= \frac{1}{I_y}\left\{\dot{\phi}\dot{\psi}(I_z - I_x) - K_{fay}\dot{\theta}^2 - J_r\varpi\dot{\phi} + dU_3\right\} \\
\ddot{\psi} &= \frac{1}{I_z}\left\{\dot{\theta}\dot{\phi}\left(I_x - I_y\right) - K_{faz}\dot{\psi}^2 + K_d U_4\right\} \\
\ddot{x} &= \frac{1}{m}\left\{(Cos\phi\ Sin\theta\ Cos\psi + Sin\phi\ Sin\psi)U_1 - K_{ftx}\dot{x}\right\} \\
\ddot{y} &= \frac{1}{m}\left\{(Cos\phi\ Sin\theta\ Sin\psi - Sin\phi\ Cos\psi)U_1 - K_{fty}\dot{y}\right\} \\
\ddot{z} &= \frac{1}{m}\left\{(Cos\phi\ Cos\theta)U_1 - K_{ftz}\dot{z}\right\} - g
\end{aligned}$$

Here U_1, U_2, U_3 and U_4 are control inputs and can be defined as

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} F_1 + F_2 + F_3 + F_4 \\ F_3 - F_1 \\ F_4 - F_2 \\ F_1 - F_2 + F_3 - F_4 \end{bmatrix} \tag{3-13}$$

According to [25] in case of low wind model can be written as

$$\ddot{\phi} = \frac{1}{I_x}\{\dot{\theta}\dot{\psi}(I_y - I_z) + dU_2\}$$

$$\ddot{\theta} = \frac{1}{I_y}\{\dot{\phi}\dot{\psi}(I_z - I_x) + dU_3\}$$

$$\ddot{\psi} = \frac{1}{I_z}\{\dot{\theta}\dot{\phi}(I_x - I_y) + K_d U_4\}$$

$$\ddot{x} = \frac{1}{m}\{(Cos\phi\ Sin\theta\ Cos\psi + Sin\phi\ Sin\psi)U_1\}$$

$$\ddot{y} = \frac{1}{m}\{(Cos\phi\ Sin\theta\ Sin\psi - Sin\phi\ Cos\psi)U_1\}$$

$$\ddot{z} = \frac{1}{m}\{(Cos\phi\ Cos\theta)U_1 - K_{ftz}\dot{z}\} - g$$

3.4 STATE SPACE MODEL

Let $[x_1\ x_3\ x_5\ \ x_7\ x_9\ \ x_{11]} = [x\ \ y\ \ z\ \ \phi\ \ \theta\ \ \psi]$, we get following state space model. In the next section this model will be used to develop a Simulink model.

$$\dot{x}_1 = x_2 \tag{3-14}$$

$$\dot{x}_2 = \frac{1}{m}\{(Cosx_7\ Sinx_9\ Cos\psi + Sinx_7\ Sinx_{11})U_1\} \tag{3-15}$$

$$\dot{x}_3 = x_2 \tag{3-16}$$

$$\dot{x}_4 = \frac{1}{m}\{(Cosx_7\ Sinx_9\ Sin\psi - Sinx_7\ Cosx_{11})U_1\} \tag{3-17}$$

$$\dot{x}_5 = x_6 \tag{3-18}$$

$$\dot{x}_6 = \frac{1}{m}\{(Cosx_7\ Cosx_9)U_1\} - g \tag{3-19}$$

$$\dot{x}_7 = x_8 \tag{3-20}$$

$$\dot{x}_8 = \frac{1}{I_x}\{x_{10}x_{12}(I_y - I_z) + dU_2\} \tag{3-21}$$

$$\dot{x}_9 = x_{10} \tag{3-22}$$

$$\dot{x}_{10} = \frac{1}{I_y}\{x_8 x_{12}(I_z - I_x) + dU_3\} \tag{3-23}$$

$$\dot{x}_{11} = x_{12} \tag{3-24}$$

$$\dot{x}_{12} = \frac{1}{I_z}\{x_8 x_{10}(I_x - I_y) + K_d U_4\} \tag{3-25}$$

3.5 SIMULINK MODEL

In this section a Simulink model of QR UAV will be presented. State space model derived in last section will be used to create following Simulink model. Figure 3-3 shows the Simulink model

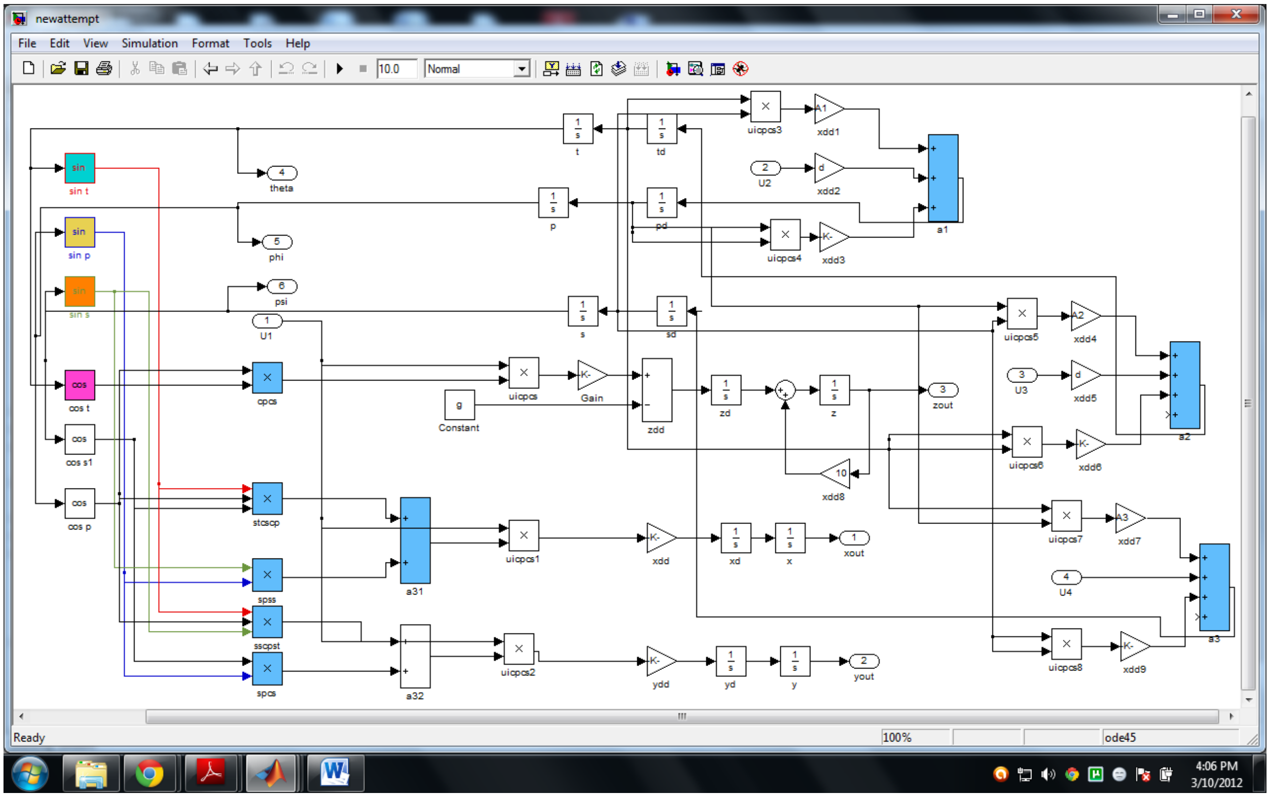

Figure 3-3 Simulink model

3.5.1 DEFINING CONSTANTS

Following MATLAB Program is written to define all parametric constants of QR UAV given in table 3-1. Which is used in simulink model of Figure 3-3.

```
m=0.486;
Ix=3.8278e-3;
Iy=3.8288e-3;
Iz=7.6566e-3;
kax=(5.5670e-4)/Ix;
kay=(5.5670e-4)/Iy;
kaz=(6.534e-4)/Iz;
g=9.8;
A1=(Iy-Iz)/Ix;
d=0.25/Ix;
A2=(Iz-Ix)/Iy;
A3=(Ix-Iy)/Iz;
Kd=3.232e-7;
```

3.6 CONCLUSION

Mathematical model of QR UAV is presented. In section 3.2 a description of system is given. Dynamic model of QR is derived using Newton-Euler's method in section 3.3. Sections 3.4 presents state space model and 3.5 covers a Simulink model of QR. This mathematical model will be used to design a controller to stabilize QR in next chapter.

CHAPTER

4 CONTROLLER DESIGN

A controller is a system which is used to modify the response of any physical system. A proper controller control strategy is necessary to use physical systems according to our requirement. Controller can be as simple as open loop or much complex system like adaptive robust controller.

4.1 INTRODUCTION

In this chapter an adaptive backstepping controller will be designed for the model developed in last chapter. Section 4.2 discusses the proposed strategy and controller design is presented in section 4.3. There are many choices for controllers. In this chapter an adaptive controller based on the concept of backstepping control and Lyapunov theory will be designed due to many advantages over other controller.

4.2 PROPOSED STRATEGY

There are many techniques in control engineering to control nonlinear systems. Feedback linearization is a most traditional technique which uses cancellation of all nonlinear components of plant to achieve desired responses. There are some useful nonlinearities which can be used to stabilize the system. To cancel these components a large control power is wasted.

Many techniques have been proposed to control uncertain plants in efficient manner. Adaptive control has been proven one of the most suitable methods. As the name suggests this control scheme uses the principle of adaptation i.e. its parameter are adjusted during the plant operation. In this method first some estimators are used to estimate uncertain parameters then a control law is used to achieve stability and good transient response. There are some other types of uncertainties such as structural uncertainties and external disturbances. There are many methods in adaptive controllers to manage these uncertainties. One of them is “certainty equivalence based design” used in [27,28]. This technique is also used to address problems related to non-smooth nonlinearities. However transient response is not satisfactory.

Backstepping control is proved very efficient technique in the synthesizing of nonlinear controllers. It was proposed in 1990 by Krstic, M., Kanellakopoulos, I., Kokotovic, and P.V [3]. It is a recursive method which divides whole design problem into a sequence of small design problems [26]. This idea deals with the use of functions of state variables as virtual inputs. It can be applied to a class of systems in lower triangular form and can be used to avoid cancellation of useful nonlinearities. This method provides a systematic procedure of constructing feedback laws and Lyapunov functions. Despite very less age of this theory it can be seen easily that this theory is being used in many research activities. Backstepping control uses Lyapunov stability theory to design a controller. Flexibility is another advantage of this scheme i.e. it avoids to cancel useful nonlinearities. Hence, it saves control effort and provides stabilization and tracking.

According to Lyapunov stability theory if there exist a positive definite function *V(x)* such that its derivative is semi negative definite then the system will be stable. If we can find a function positive definite function *V(x)* such that its derivative is negative definite then system is also asymptotically stable. More over if *V(x)* fulfills following condition then system will be asymptotically globally stable.

$$\frac{dV}{dt} < 0 \text{ and } V(x) \to \infty \text{ when } \|x\| \to \infty$$

The control strategy proposed in this section is the combination of adaptive control and backstepping. Adaptive backstepping controller uses backstepping control law and adjusts its parameters according to the desired response. Adaptive controllers are very useful in the controlling uncertain nonlinear plants. Application of these controllers is proved successful in [4] and others.

4.3 CONTROLLER DESIGN

In this section an adaptive backstepping controller will be designed for the model derived in last chapter. Here we rewrite the model equations.

$$\dot{x}_1 = x_2 \tag{3-13}$$

$$\dot{x}_2 = \frac{1}{m}\{(Cosx_7\, Sinx_9\, Cos\psi + Sinx_7\, Sinx_{11})U_1\} \tag{3-14}$$

$$\dot{x}_3 = x_2 \tag{3-15}$$

$$\dot{x}_4 = \frac{1}{m}\{(Cosx_7\, Sinx_9\, Sin\psi - Sinx_7\, Cosx_{11})U_1\} \tag{3-16}$$

$$\dot{x}_5 = x_6 \tag{3-17}$$

$$\dot{x}_6 = \frac{1}{m}\{(Cosx_7\, Cosx_9)U_1\} - g \tag{3-18}$$

$$\dot{x}_7 = x_8 \tag{3-19}$$

$$\dot{x}_8 = \frac{1}{I_x}\{x_{10}x_{12}(I_y - I_z) + dU_2\} \tag{3-20}$$

$$\dot{x}_9 = x_{10} \tag{3-21}$$

$$\dot{x}_{10} = \frac{1}{I_y}\{x_8x_{12}(I_z - I_x) + dU_3\} \tag{3-22}$$

$$\dot{x}_{11} = x_{12} \tag{3-23}$$

$$\dot{x}_{12} = \frac{1}{I_z}\{x_8x_{10}(I_x - I_y) + K_dU_4\} \tag{3-24}$$

4.3.1 CONTROL OF ALTITUDE

First of all a control law will be designed for altitude. Here a model uncertainty is included in equation (3-17)

$$\dot{x}_5 = x_6 + \varepsilon x_5 \quad (4\text{-}1)$$

Where εx_5 is a model uncertainty that shows that velocity in the direction of z-axis has some dependence on altitude.

Introducing new coordinates z_1 and z_2.

$$z_1 = x_5 - z_r \quad (4\text{-}2)$$

$$z_2 = x_6 - v_1 - \dot{z}_r \quad (4\text{-}3)$$

Here v_1 is a virtual control input and z_r is reference signal of altitude. Differentiating (4-2) yields

$$\dot{z}_1 = \dot{x}_5 - \dot{z}_r$$

or

$$\dot{z}_1 = z_2 + v_1 + \varepsilon x_5 \quad (4\text{-}4)$$

Here ε is unknown. To estimate its value and design a controller, we define a Lyapunov function.

$$V_1(x) = \frac{1}{2}{z_1}^2 + \frac{1}{2}\lambda\tilde{\varepsilon}^2 \quad (4\text{-}5)$$

Where $\tilde{\varepsilon}$ is estimation error and defined as $\tilde{\varepsilon} = \varepsilon - \hat{\varepsilon}$. $\hat{\varepsilon}$ denotes the estimated value of ε.

Differentiating (4-5)

$$\dot{V}_1(x) = z_1\dot{z}_1 + \lambda\tilde{\varepsilon}\frac{d\tilde{\varepsilon}}{dt}$$

$$= z_1(z_2 + v_1 + \varepsilon x_5) - \lambda\tilde{\varepsilon}\frac{d\hat{\varepsilon}}{dt}$$

$$= z_1 z_2 + z_1 v_1 + z_1 x_5(\tilde{\varepsilon} + \hat{\varepsilon}) - \lambda\tilde{\varepsilon}\frac{d\hat{\varepsilon}}{dt}$$

$$= z_1 z_2 + z_1 v_1 + z_1 x_5\tilde{\varepsilon} + z_1 x_5\hat{\varepsilon} - \lambda\tilde{\varepsilon}\frac{d\hat{\varepsilon}}{dt}$$

$$= z_1 z_2 + z_1(v_1 + x_5\hat{\varepsilon}) + \tilde{\varepsilon}(z_1 x_5 - \lambda\frac{d\hat{\varepsilon}}{dt}) \quad (4\text{-}6)$$

Setting $-c_1 z = v_1 + x_5\hat{\varepsilon}$ or $v_1 = -c_1 z - x_5\hat{\varepsilon}$ and $z_1 x_5 - \lambda\frac{d\hat{\varepsilon}}{dt} = 0$ or $\frac{d\hat{\varepsilon}}{dt} = \frac{1}{\lambda}z_1 x_5$

Where $c_1 \geq 0$

Eq (4-6) implies

$$\dot{V}_1(x) = z_1 z_2 - c_1{z_1}^2 \quad (4\text{-}7)$$

Now

$$\dot{z}_2 = \dot{x}_6 - \dot{v}_1 - \ddot{z}_r$$

$$\dot{z}_2 = \frac{1}{m}\{(Cosx_7\ Cosx_9)U_1\} - g - (\frac{\partial v_1}{\partial x_5}\dot{x}_5 + \frac{\partial v_1}{\partial \hat{\varepsilon}}\frac{d\hat{\varepsilon}}{dt}) - \ddot{z}_r$$

$$\dot{z}_2 = \frac{1}{m}\{(Cosx_7\ Cosx_9)U_1\} - g - \frac{\partial v_1}{\partial x_5}(x_6 + \varepsilon x_5) - \frac{\partial v_1}{\partial \hat{\varepsilon}}\left(\frac{1}{\lambda}z_1 x_5\right) - \ddot{z}_r$$

$$\dot{z}_2 = \frac{1}{m}\{(Cosx_7\ Cosx_9)U_1\} - g - \frac{\partial v_1}{\partial x_5}x_6 - \varepsilon x_5\frac{\partial v_1}{\partial x_5} - \frac{\partial v_1}{\partial \hat{\varepsilon}}(\frac{1}{\lambda}z_1 x_5) - \ddot{z}_r \qquad (4\text{-}8)$$

Now we define another Lyapunov candidate

$$V_2(x) = V_1(x) + \frac{1}{2}{z_2}^2$$

$$\dot{V}_2(x) = z_1 z_2 - c_1 {z_1}^2 + z_2 \dot{z}_2$$

$$\dot{V}_2(x) = -c_1{z_1}^2 + z_2[\frac{1}{m}\{(Cosx_7\ Cosx_9)U_1\} + z_1 - g - \frac{\partial v_1}{\partial x_5}x_6 - \varepsilon x_5\frac{\partial v_1}{\partial x_5} - \frac{\partial v_1}{\partial \hat{\varepsilon}}(\frac{1}{\lambda}z_1 x_5) - \ddot{z}_r] \qquad (4\text{-}9)$$

Now it is possible to choose a control law for U_1 to cancel all other terms except $-c_1{z_1}^2$ to make $\dot{V}_2(x)$ negative definite. As we don't have exact value of ε its estimate will be used. Control law is given by

$$\frac{1}{m}\{(Cosx_7\ Cosx_9)U_1\} - g = -z_1 - c_2 + \frac{\partial v_1}{\partial x_5}x_6 + \hat{\varepsilon}x_5\frac{\partial v_1}{\partial x_5} + \frac{\partial v_1}{\partial \hat{\varepsilon}}\left(\frac{1}{\lambda}z_1 x_5\right) + \ddot{z}_r$$

$$U_1 = \frac{m}{Cosx_7\,Cosx_9}\{-z_1 - c_2 + \frac{\partial v_1}{\partial x_5}x_6 + \hat{\varepsilon}x_5\frac{\partial v_1}{\partial x_5} + \frac{\partial v_1}{\partial \hat{\varepsilon}}\left(\frac{1}{\lambda}z_1 x_5\right) + \ddot{z}_r + g\}$$

Using value of *U₁* in equation (4.9), we get

$$\dot{V}_2(x) = -c_1{z_1}^2 - c_2{z_2}^2 - x_5\frac{\partial v_1}{\partial x_5}(\varepsilon - \hat{\varepsilon})$$

It can be easily seen that it is impossible to cancel $(\varepsilon - \hat{\varepsilon})$. Now a new estimate of ε i.e. ε_2 is needed to eliminate this. With this estimate control law becomes

$$U_1 = \frac{m}{Cosx_7\ Cosx_9}\{-z_1 - c_2 + \frac{\partial v_1}{\partial x_5}x_6 + \hat{\varepsilon}_2 x_5\frac{\partial v_1}{\partial x_5} + \frac{\partial v_1}{\partial \hat{\varepsilon}}\left(\frac{1}{\lambda}z_1 x_5\right) + \ddot{z}_r + g\} \qquad (4\text{-}10)$$

Using value of *U₁* in equation (4.8), we get

$$\dot{z}_2 = -z_1 - c_2 z_2 - x_5\frac{\partial v_1}{\partial x_5}(\varepsilon - \hat{\varepsilon}_2)$$

Where $c_2 \geq 0$

Let's define a third Lyapunov candidate function.

$$V_3(x) = V_1(x) + \frac{1}{2}{z_2}^2 + \frac{1}{2}\lambda{\tilde{\varepsilon}_2}^2$$

Differentiating and simplifying we get

$$\dot{V}_3(x) = -c_1{z_1}^2 - c_2{z_2}^2 - \lambda\tilde{\varepsilon}_2(\frac{d\hat{\varepsilon}_2}{dt} + \lambda^{-1}\frac{\partial v_1}{\partial x_5}x_5 z_2)$$

Selecting an update law

$$\frac{d\hat{\varepsilon}_2}{dt} = -\lambda^{-1}\frac{\partial v_1}{\partial x_5}x_5 z_2$$

yields $\dot{V}_3(x) = -c_1{z_1}^2 - c_2{z_2}^2$ Which is negative definite and guarantees that control law (4-10) stabilizes the altitude.

4.3.2 CONTROL OF YAW ANGLE

To control Yaw angle, related equations of state space model are given as

$$\dot{x}_{11} = x_{12} \tag{4-11}$$

$$\dot{x}_{12} = \frac{1}{I_z}\{x_8 x_{10}(I_x - I_y) + K_d U_4\} + \rho x_{11} \tag{4-12}$$

Where ρx_{11} represents model uncertainty. This uncertainty is included under an assumption that acceleration along *z* axis also depends on yaw position. Introducing new coordinates z_3 and z_4.

$$z_3 = x_{11} - \psi_r \quad ` \tag{4-13}$$

$$z_4 = x_{12} - v_2 - \dot{\psi}_r \tag{4-14}$$

Here v_2 is a virtual control input and z_r is reference signal of altitude.

Differentiating (4-13) yields

$$\dot{z}_3 = \dot{x}_{11} - \dot{z}_r$$

$$\dot{z}_3 = z_4 + v_2 \tag{4-15}$$

Here ρ is unknown. To estimate its value and design a controller, we define a Lyapunov candidate.

$$V_4(x) = \frac{1}{2}{z_3}^2 + \frac{1}{2}\lambda_2\tilde{\rho}^2 \tag{4-16}$$

Where $\tilde{\rho}$ is estimation error and defined as $\tilde{\rho} = \rho - \hat{\rho}$. $\hat{\rho}$ denotes the estimated value of ρ.

Differentiating (4-16)

$$\dot{V}_4(x) = z_3\dot{z}_3 + \lambda_2\tilde{\rho}\frac{d\tilde{\rho}}{dt}$$

$$\dot{V}_4(x) = z_3(z_4 + v_2) - \lambda\tilde{\rho}\frac{d\hat{\rho}}{dt}$$

$$\dot{V}_4(x) = z_3 z_4 + z_3 v_2 - \lambda\tilde{\rho}\frac{d\hat{\rho}}{dt} \tag{4-17}$$

Setting $-c_3 z_3 = v_2$ and $\lambda\tilde{\rho}\frac{d\hat{\rho}}{dt} = 0$
Where $c_3 \geq 0$

Eq. 4.17 implies $\dot{V}_4(x) = z_3 z_4 - c_3 {z_3}^2$ (4-18)

Now $\dot{z}_4 = \dot{x}_{12} - \dot{v}_2 - \ddot{\psi}_r$

$$\dot{z}_4 = \frac{1}{I_z}\{x_8 x_{10}(I_x - I_y) + K_d U_4\} + \rho x_{11} - (\frac{\partial v_2}{\partial x_{11}}\dot{x}_{11} + \frac{\partial v_2}{\partial \hat{\rho}}\frac{d\hat{\rho}}{dt}) - \ddot{\psi}_r$$

$$= \frac{1}{I_z}\{x_8 x_{10}(I_x - I_y) + K_d U_4\} + \rho x_{11} - \frac{\partial v_2}{\partial x_{11}} x_{12} - \frac{\partial v_2}{\partial \hat{\rho}}\frac{d\hat{\rho}}{dt}) - \ddot{\psi}_r$$

$$\dot{z}_4 = \frac{1}{I_z}\{x_8 x_{10}(I_x - I_y) + K_d U_4\} + \rho x_{11} - \frac{\partial v_2}{\partial x_{11}} x_{12} - \ddot{\psi}_r$$

Now we define another Lyapunov candidate

$$V_5(x) = V_4(x) + \frac{1}{2}{z_4}^2$$

$$\dot{V}_5(x) = z_3 z_4 - c_3 {z_3}^2 + z_4 \dot{z}_{42}$$

$$\dot{V}_5(x) = -c_3 {z_3}^2 + z_4[\frac{1}{I_z}\{x_8 x_{10}(I_x - I_y) + K_d U_4\} + z_3 - \frac{\partial v_2}{\partial x_{11}} x_{12} - \rho x_{11} - \ddot{z}_r] \quad (4\text{-}19)$$

It is possible to choose a control law for U_1 to cancel all other terms except $-c_3 {z_3}^2$ to make $\dot{V}_5(x)$ negative definite. As we don't have exact value of ρ, its estimate will be used.
Control law is given by

$$\left[\frac{1}{I_z}\{x_8 x_{10}(I_x - I_y) + K_d U_4\} + z_3 - \frac{\partial v_2}{\partial x_{11}} x_{12} - \rho x_{11} - \ddot{z}_r\right] = 0$$

$$U_4 = \frac{I_z}{K_d}\left[-z_3 + \frac{\partial v_2}{\partial x_{11}} x_{12} + \hat{\rho} x_{11} + \ddot{z}_r\right] - \frac{x_8 x_{10}}{K_d}(I_x - I_y)$$

Here $\hat{\rho}$ is used as an estimate of ρ . Using value of U_4 in (4-19) implies

$$\dot{V}_5(x) = -c_3 {z_3}^2 - c_4 {z_4}^2 - x_{11}\frac{\partial v_1}{\partial x_{11}}(\rho - \hat{\rho})$$

It is clear that $(\rho - \hat{\rho})$ can't be canceled. Now a new estimate of ρ i.e. $\hat{\rho}_2$ will be used to eliminate this term.

Now control law has following form.

$$U_4 = \frac{I_z}{K_d}\left[-z_3 + \frac{\partial v_2}{\partial x_{11}} x_{12} + \hat{\rho}_2 x_{11} + \ddot{z}_r\right] - \frac{x_8 x_{10}}{K_d}(I_x - I_y) \quad (4\text{-}20)$$

and $\dot{z}_4 = -z_3 - c_4 z_4 + x_{11}(\varepsilon - \hat{\varepsilon}_2)$

Where $c_4 \geq 0$

Let's define a third Lyapunov candidate function.

$$V_6(x) = V_6(x) + \frac{1}{2}{z_4}^2 + \frac{1}{2}\lambda_2{\tilde{\rho}_2}^2$$

Differentiating and simplifying we get

$$\dot{V}_6(x) = -c_3{z_3}^2 - c_4{z_4}^2 - \lambda_2\tilde{\rho}_2(\frac{d\hat{\rho}_2}{dt} - {\lambda_2}^{-1}x_{11}z_4)$$

Selecting an update law

$$\frac{d\hat{\rho}_2}{dt} = \frac{1}{\lambda_{2s}}x_{11}z_4$$

yields $\dot{V}_6(x) = -c_3{z_3}^2 - c_4{z_4}^2$. Which is negative definite and guarantees that control law (4-20) stabilizes the altitude.

4.3.3 CONTROL OF ROLL AND PITCH ANGLE

Strategy given in last sub section can be applied to control roll and pitch angle. For roll angle control laws are given by

$$U_2 = \frac{I_x}{d}\left[-z_5 + \frac{\partial v_3}{\partial x_7}x_8 + \hat{\eta}_2 x_7 + \ddot{\phi}_r\right] - \frac{x_{12}x_{10}}{d}\left(I_y - I_z\right) \quad (4\text{-}21)$$

$$z_5 = x_7 - \phi_r \quad (4\text{-}22)$$

$$z_6 = x_8 - v_3 - \dot{\phi}_r \quad (4\text{-}23)$$

$$\frac{d\hat{\eta}_2}{dt} = {\lambda_3}^{-1}x_7 z_6 \quad (4\text{-}24)$$

$$v_3 = -c_5 z_5 \quad (4\text{-}25)$$

Similarly for pitch

$$U_3 = \frac{I_y}{d}\left[-z_7 + \frac{\partial v_4}{\partial x_9}x_{10} + \hat{\mu}_2 x_9 + \ddot{\theta}_r\right] - \frac{x_{12}x_8}{d}\left(I_z - I_x\right) \quad (4\text{-}26)$$

$$z_7 = x_9 - \theta_r \quad (4\text{-}27)$$

$$z_8 = x_{10} - v_4 - \dot{\theta}_r \quad (4\text{-}28)$$

$$\frac{d\hat{\mu}_2}{dt} = {\lambda_4}^{-1}x_9 z_8 \quad (4\text{-}29)$$

$$v_4 = -c_7 z_7 \quad (4\text{-}30)$$

4.4 CONCLUSION

Section 4.1 provides an introduction to the topics presented in this chapter. A brief comparison of different control techniques is given in section 4.2. Section 4.3 deals with the designing of controllers. Four control laws are derived to track altitude and Euler angles of QR. To demonstrate the validity of this controller, MATLAB simulations will be performed in next chapter.

CHAPTER

5 SIMULATIONS AND RESULTS

Simulation is a very useful technique used to imitate the behavior of a system or process over time. It is widely used as an analyzing tool in not only Physical sciences but also in natural and social sciences. Simulation provides a deep insight into systems and to approximate the response of systems which are too complex for exact solution. There are many techniques and tools for simulation e.g. ANSYS, MATLAB etc.

5.1 INTRODUCTION

This chapter deals with the simulation of model of Quadrotor with and without controller design. Main objective of discussion is to validate the controller designed in last chapter. Section 5.2 covers an introduction to the software. Section 5.2 presents open loop responses. Simulink models and MATLAB programs are given in section 5.3. Simulation results with some discussion are presented in section 5.4.

5.2 MATLAB

MATLAB i.e. Matrix Laboratory is a very popular and modern simulation tool. Basically it is an interpreted language of fourth generation developed by a US company Mathworks. There is no need to write a complex program in MATLAB as there are many toolboxes and built in functions are available. SIMULINK i.e. a part of MATLAB is a very efficient environment for designing and simulating dynamic systems. It contains a large verity of predefined blocks and a graphical interface to manage block diagrams. SIMULINK provides different simulation modes such as rapid, normal etc. and full access to MATLAB for analysis and visualization of results. These features motivated us to use MATLAB SIMULINK environment as a simulation tool [31]

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5.3 SIMULINK MODELS

In this section SIMULINK model of all controllers is given. These models will be used to simulate the closed loop system.

5.3.1 ALTITUDE CONTROLLER

Figure 5-1 shows a Simulink model of altitude controller given by equations (4-2), (4-3) and (4-10).

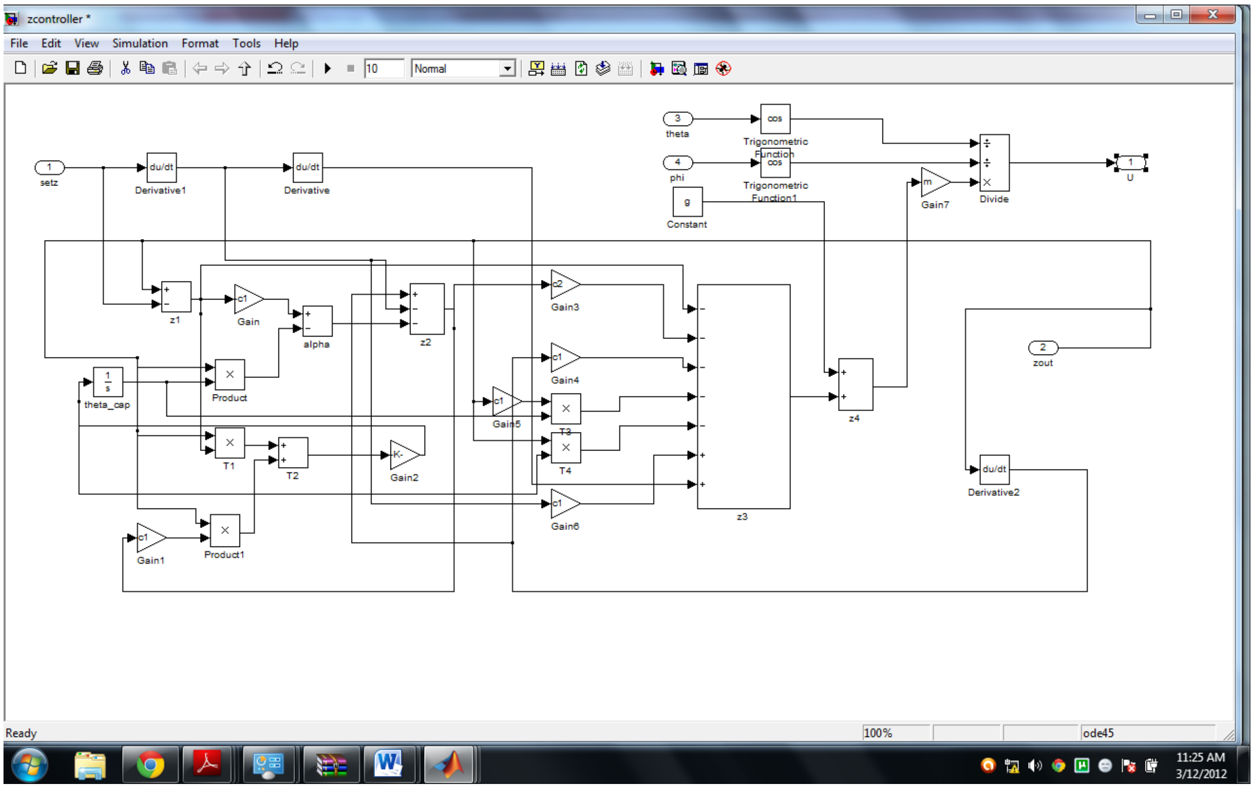

Figure 5-1 Controller for altitude

5.3.2 YAW CONTROLLER

Controller described by equations (4-13), (4-14) and (4-20) is yaw controller. This controlled is modeled in simulink as shown in figure 5-2.

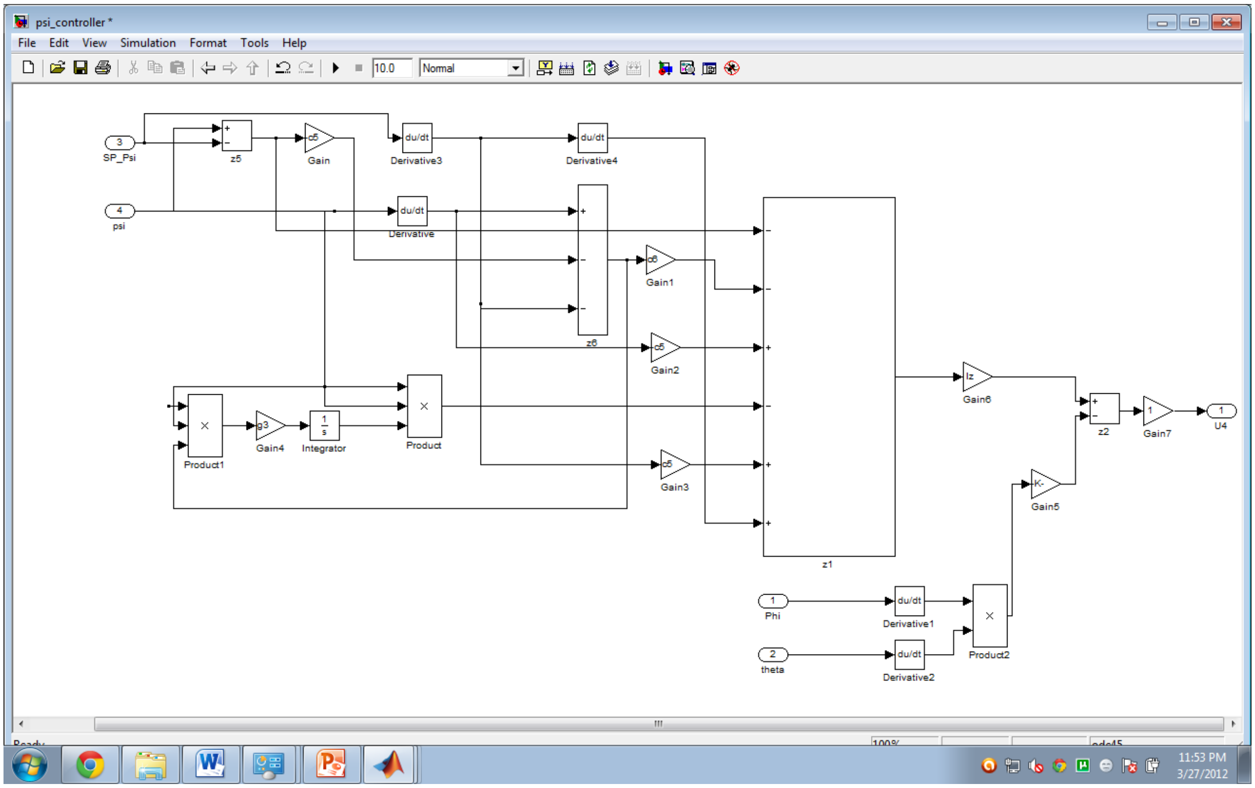

Figure 5-2 Controller for Yaw

5.3.3 ROLL CONTROLLER

Roll controller is shown in figure 5-3. This SIMULINK model is based on equations (4-26) to (4-30) derived in chapter 4.

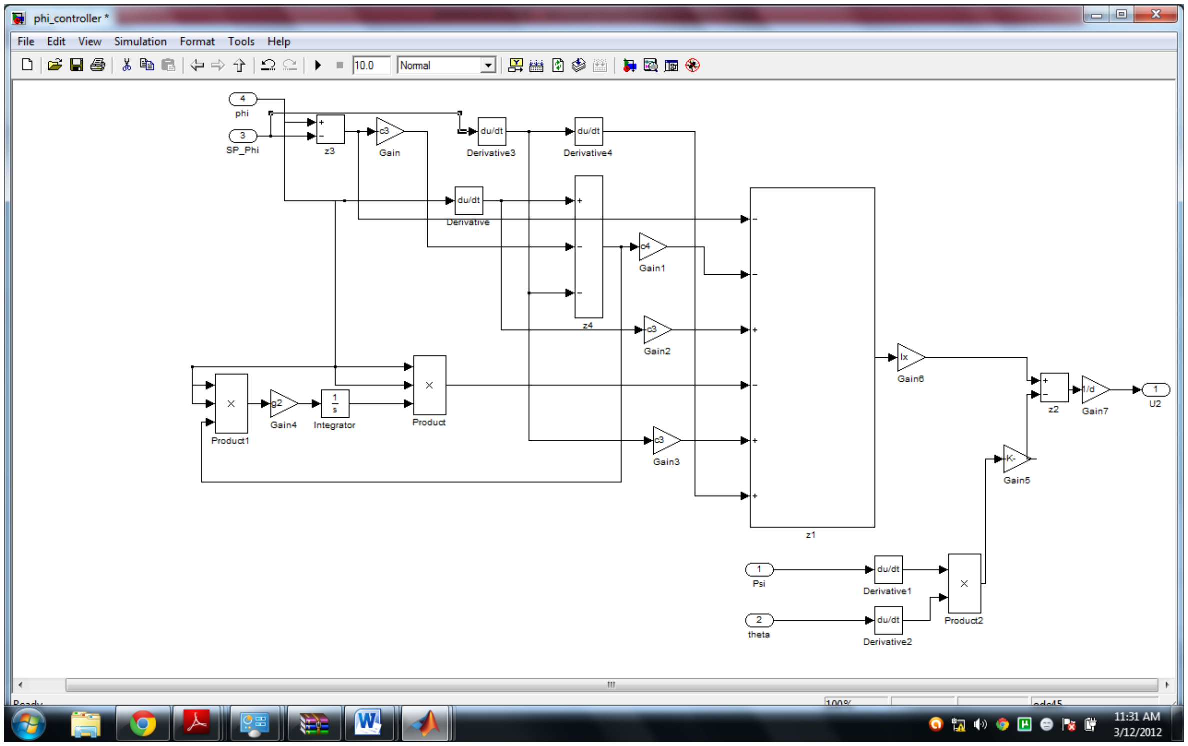

Figure 5-3 Controller for Roll

5.3.4 PITCH CONTROLLER

Last Simulink model is shown in figure (5-4). This figure represents the roll controller. This Controller is given by equations (4-21 to 4-25)

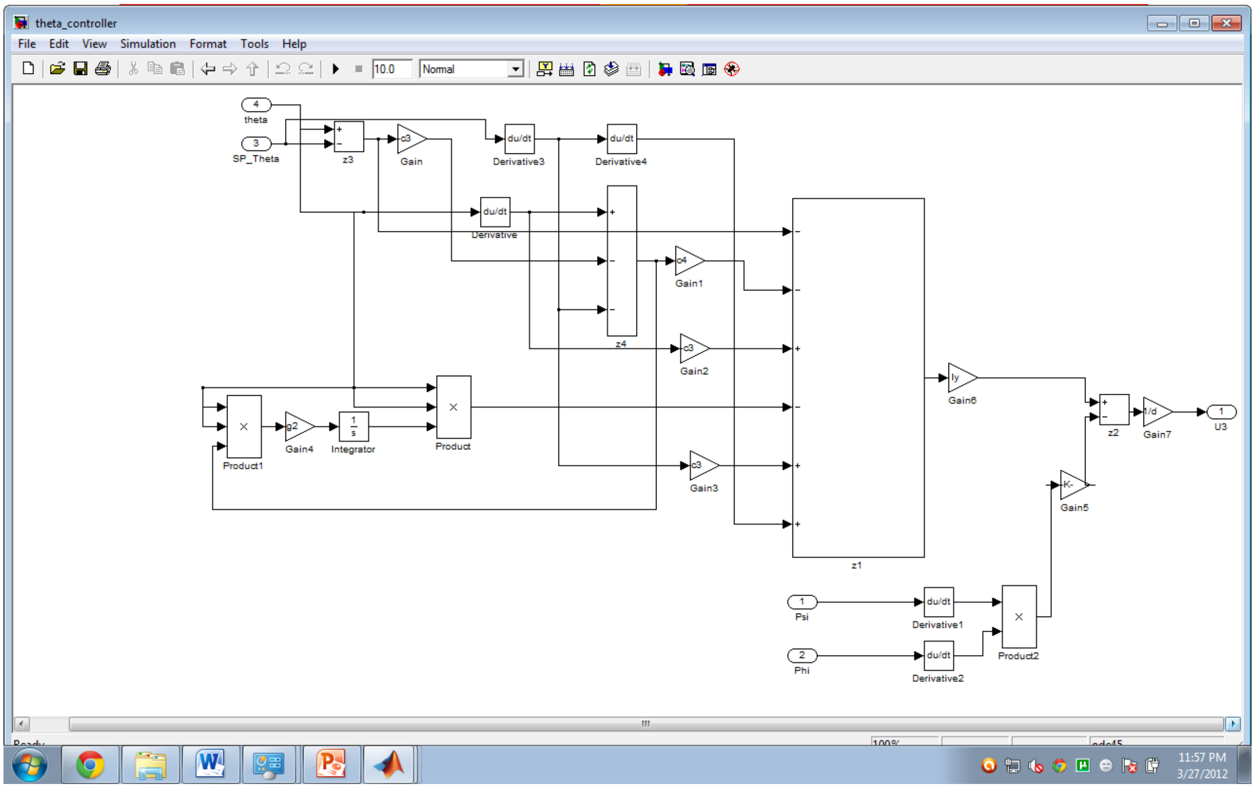

Figure 5-4 Controller for Pitch

5.4 OPEN LOOP RESPONSE

First of all model of QR UAV is simulated without any controller. Step signals are applied on all inputs and responses are noted. Fig 5-5 shows the SIMULINK model used to find open loop response. Model QR_mdl is same model given in figure 3-3.

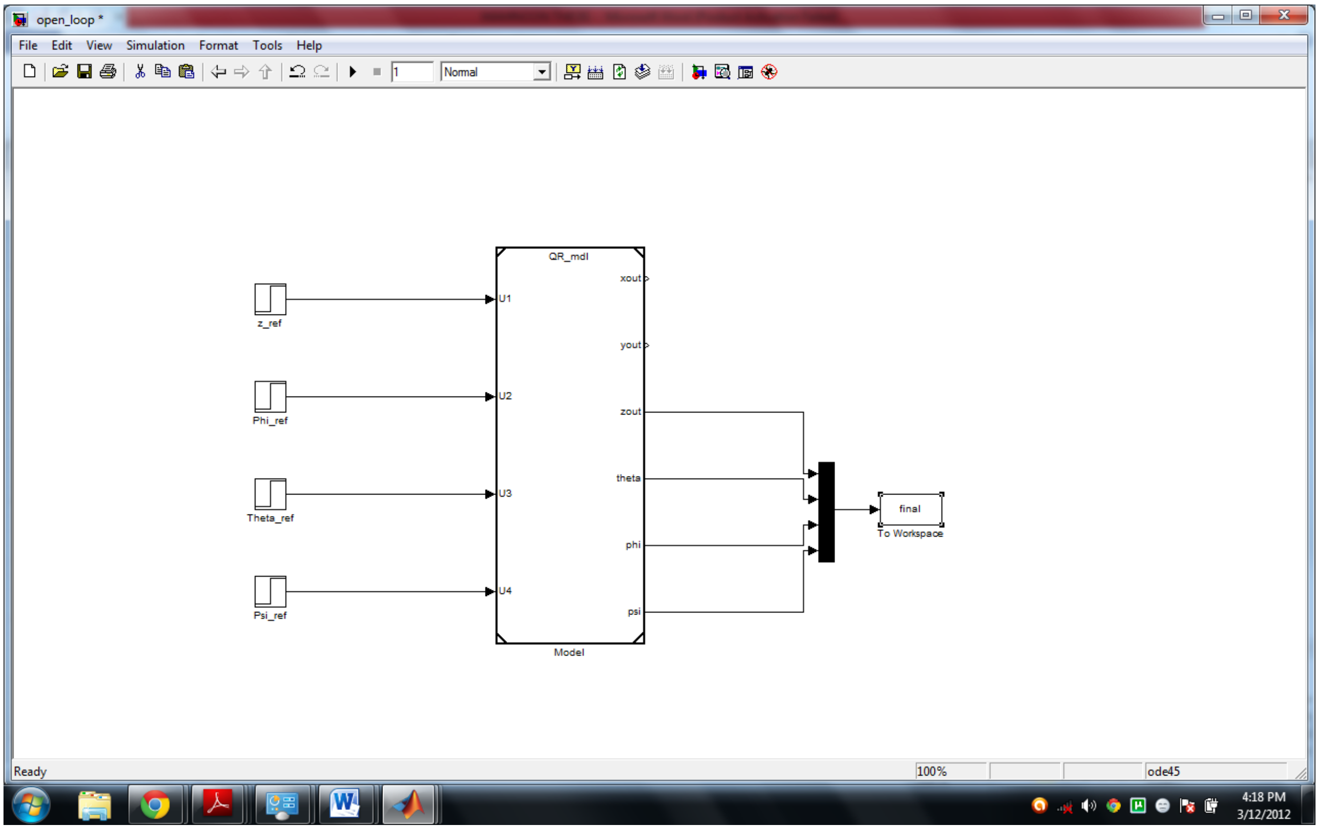

Figure 5-5 Simulink model to find open loop response

Responses found from simulations are as given here.

5.4.1 RESPONSE OF ALTITUDE

To obtain open loop response of altitude a unit step signal was applied on U_1. Figure 5-6 shows the response.

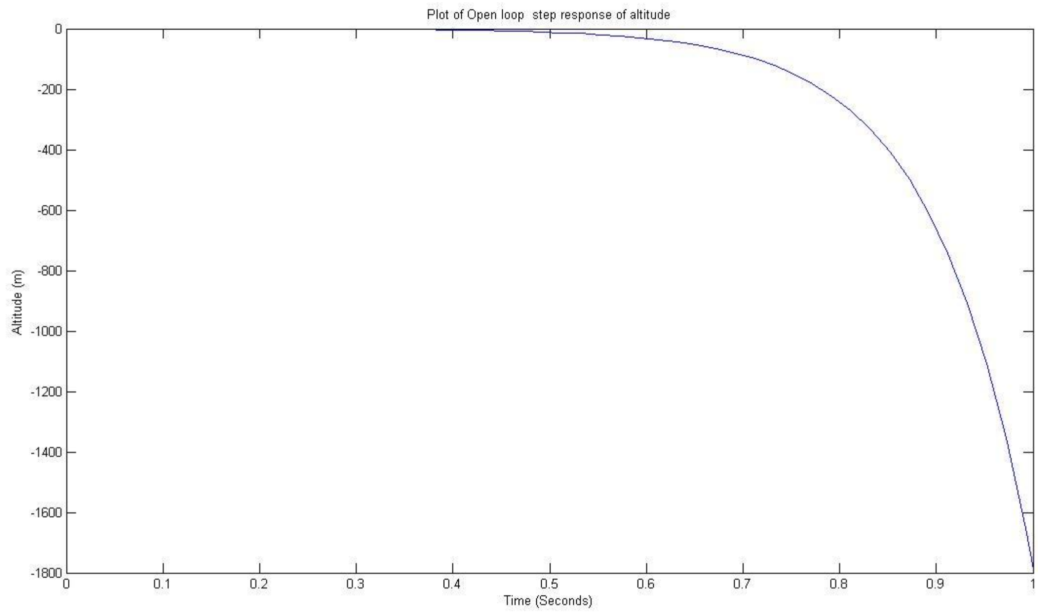

Figure 5-6 Open loop response of altitude

As expected, presence of two integrators made the plant unstable. Figure (5-6) shows that altitude attains a value of 1800m in 1 second. Thus instability of altitude is confirmed.

5.4.2 RESPONSE OF YAW

To get open loop response of yaw, a unit step is applied on U_4. Response obtained is given in figure 5-7.

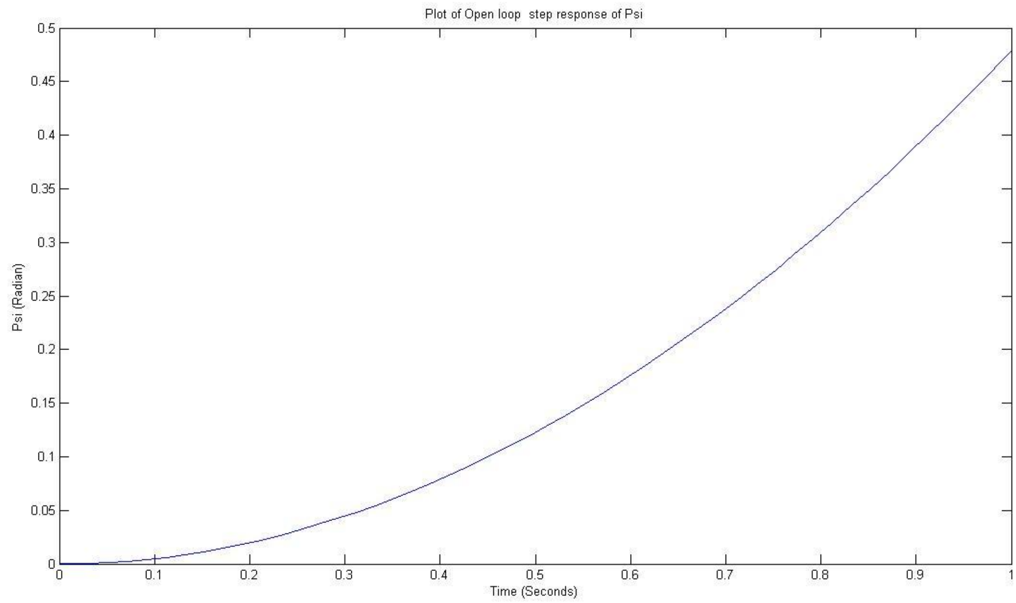

Figure 5-7 Open loop response of Yaw

It is cleared that yaw angles grows with time if QR is operated without any controller. Thus open loop response of yaw is unstable.

5.4.3 RESPONSE OF PITCH

In this subsection open loop pitch response will be presented. To get this response a unit step is applied on Control input U_3. Figure 5-8 exhibits the obtained response.

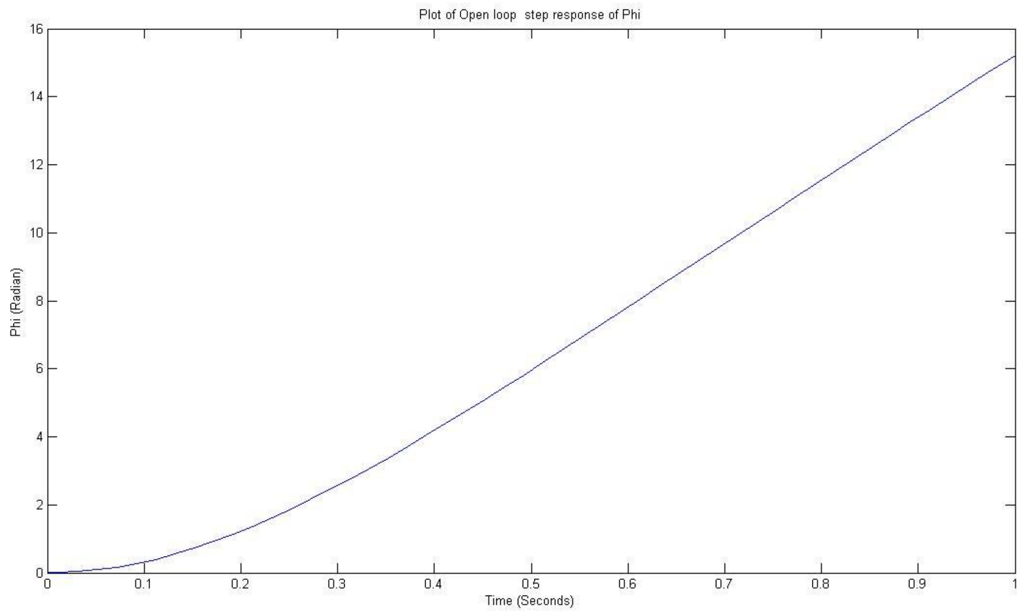

Figure 5- 8 Open loop response of pitch

Above response provides sufficient reasons to conclude that open loop pitch response of QR is unstable.

5.4.4 RESPONSE OF ROLL

This subsection demonstrates the open loop response of roll. Like last simulation a unit step is applied on U_3. Response is given in Figure 5-9.

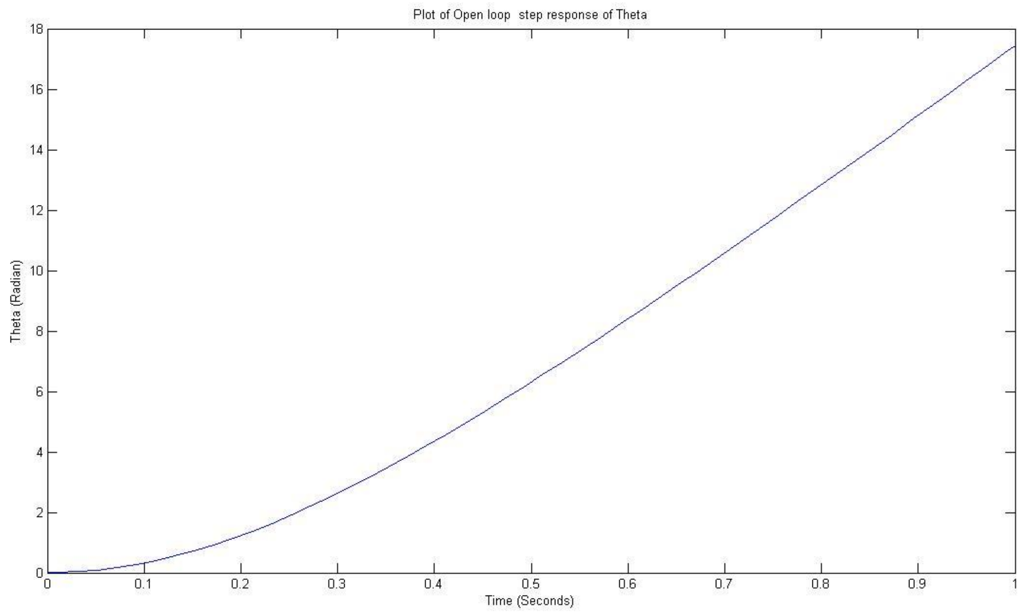

Figure 5-9 Open loop response of roll

Like other positions roll value rises continuously in response of unit step signal. Hence roll value is unstable.

From all open loop responses it can be concluded that QR UAV is an unstable plant if operated without a proper control strategy.

5.5 CLOSED LOOP RESPONSE

In this section response of QR UAV with adaptive backstepping controller on different set points is presented. As it has been shown that open loop step response of QR UAV is not satisfactory, a controller is desired to guarantee its proper operation. In this section we are using a QR plant with same model uncertainties which were discussed in last chapter during the controller design. Main objective of these simulations is to demonstrate the effectiveness of designed controller.

Model given in figure 5-10 will be used to perform closed loop simulation. Responses are taken on different set points by setting $\lambda = \lambda_i = 1;\ \forall\ i = 1,2,3$. In this figure QR_mdl block represents the model of quadrotor represented by equations (3-13 to 3-24) and uncertainties included in chapter 4. Other our blocks represent four controllers derived in chapter 4 and given by equations (4-10, 4-20, 4-21 and 4-26). These controllers are shown in Figures 5-1 to 5-4.

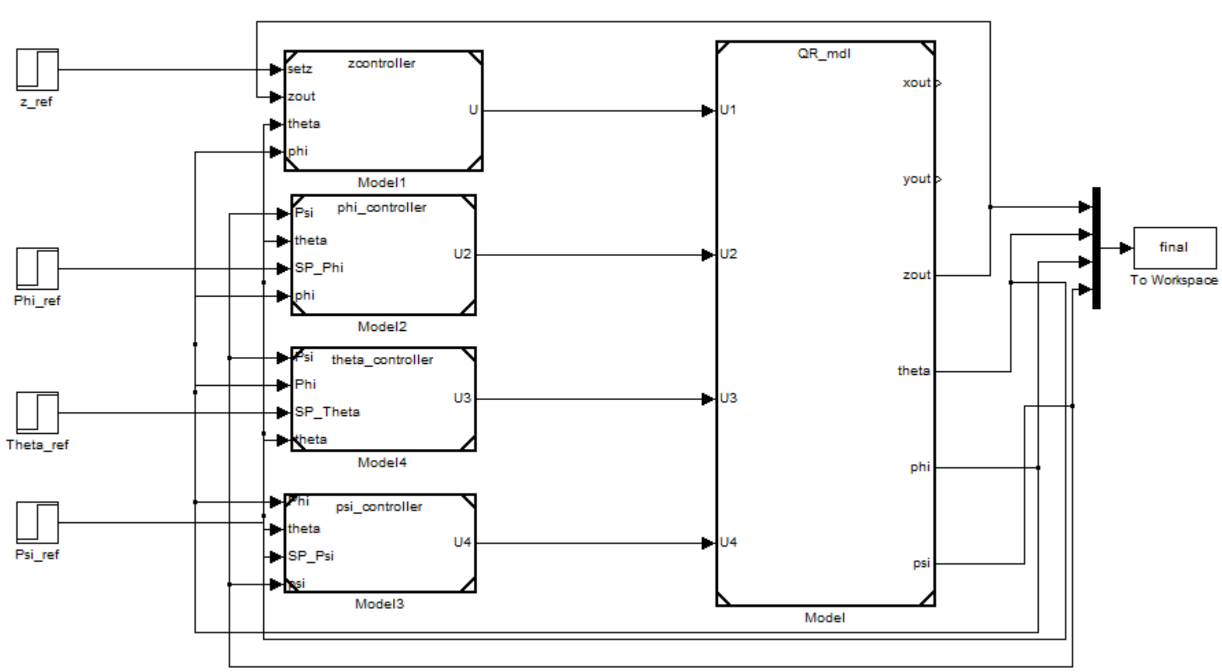

Figure 5-10 Simulink model for closed loop simulations

5.5.1 RESPONSE OF ALTITUDE

Figure 5-11 shows the response of altitude with set point is 1m. Uncertainty ε is set to a random value between 0 and 10 sec^{-1}.

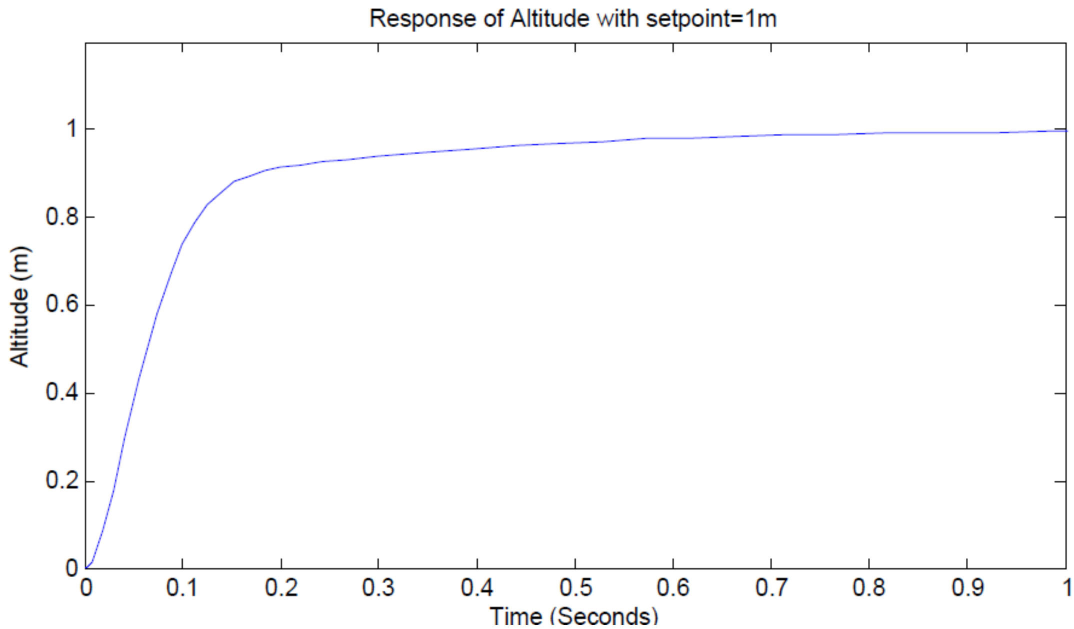

Figure 5-11 Altitude with Set point=1m

Figure shows that response is excellent only 0.3 sec settling time with no overshoot.

Now it is necessary to check the validity of controller on some higher value of set point. So second time system will be simulated with Set point=5m.

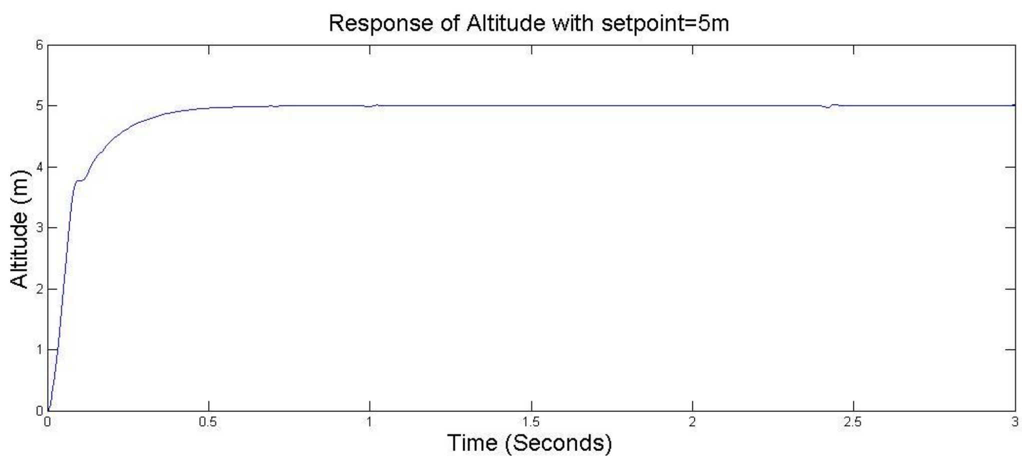

Figure 5-12 Altitude with Set point=5m

Here settling time is found to be 0.4 seconds and steady state error is 0. This response shows that system tracks higher value of set point equally good.

One more response on a small value of set point is also taken to confirm the validity of controller on any reference value. Figure 5-13 shows the response with reference signal of 0.5 m.

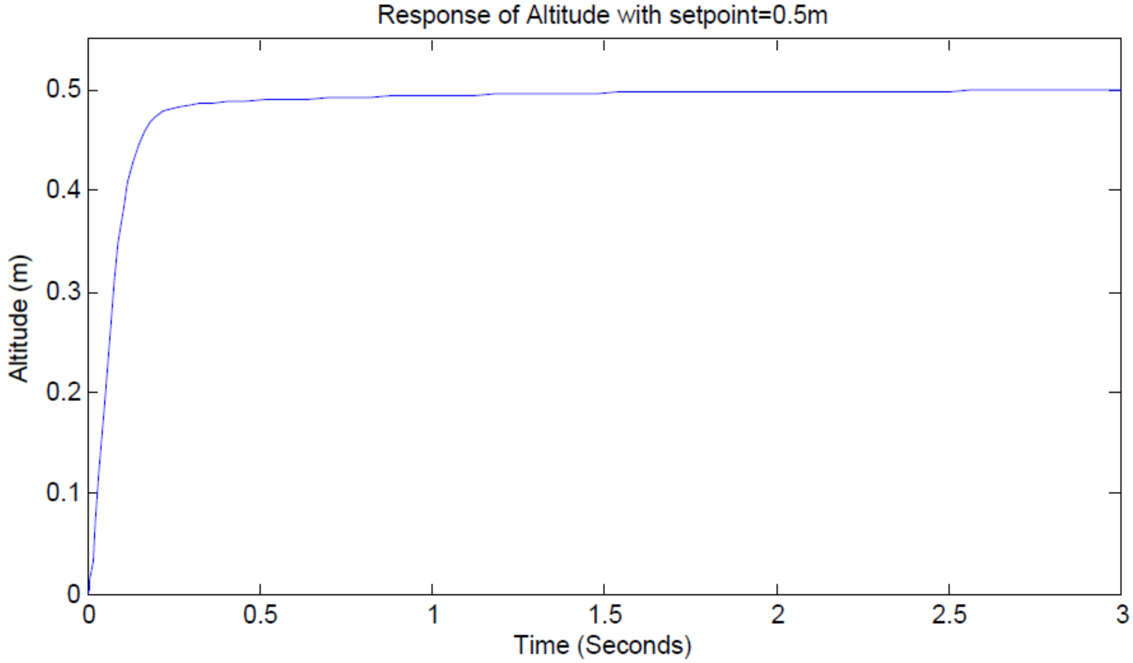

Figure 5-13 Altitude with Set point=0.5m

From the responses in figures 5-11 to 5-13 it can be concluded that controller is efficient to reject all disturbances due to model uncertainties and track the altitude command signal with very small value of settling time and no overshoot. Thus these results confirm the theoretical analysis performed by Lyapunov theorem in chapter 4.

5.5.2 RESPONSE OF YAW ANGLE

In this subsection response of yaw position of QR is being presented in presence of uncertainties defined in chapter 4 and different set points. 3 responses are taken on different reference signals. Figure 5-14 exhibits the response of yaw angle with set point=0.5 Radian.

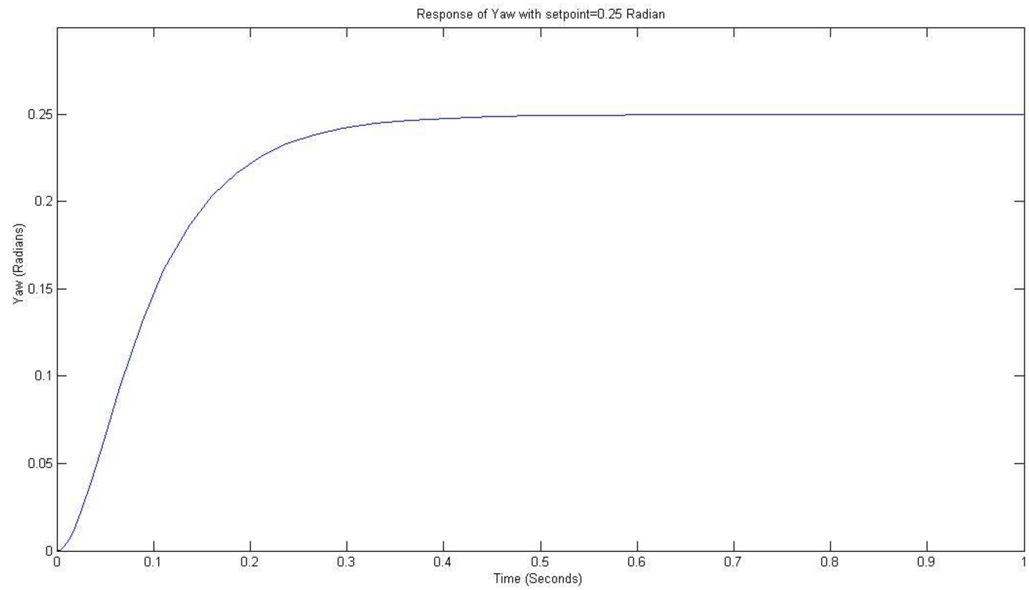

Figure 5-14 Yaw angle with set point=0.5Radians

Figure shows that controller stabilizes the yaw orientation at the reference input i.e. 0.5 Radians. No overshoot is observed with settling time = 0.3 seconds.

To have a detailed analysis of controller another response of system is taken with set point of 0.25 Rad. Following figure shows the response of controller.

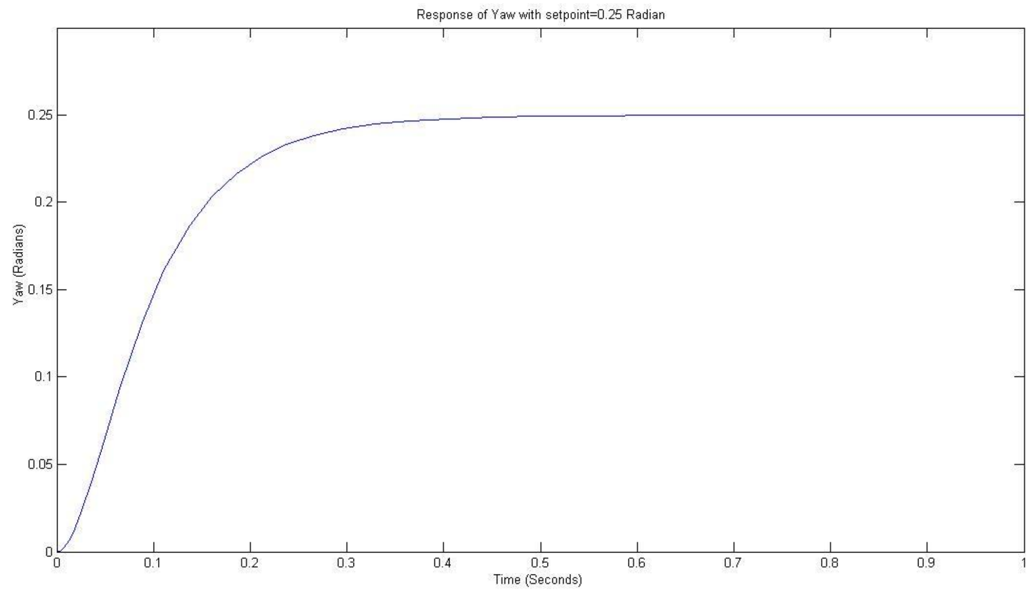

Figure 5-15 Yaw angle with set point=0.25Radians

Here settling time is 0.4 seconds and there is no steady state error and overshoot. Above figure shows that controller has ability to maintain Yaw orientation on small value of reference signal.

To check whether controller has ability to maintain QR at 0 radian Yaw angle a reference signal of 0 Radian is applied and response is noted. Here initial condition is set at 0.2 Rad. Simulation results show that Controller has successfully regulated the yaw attitude at 0 Rad.

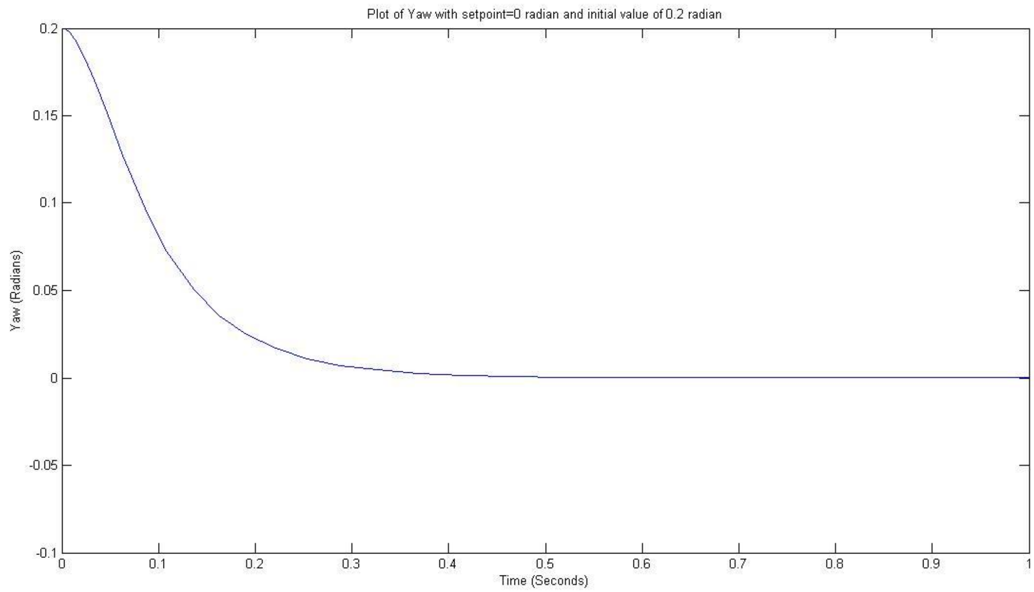

Figure 5-16 Yaw angle with set point=0 Radians with initial condition of 0.2 Rad

It can be noted from figure that there is no steady state error and settling time is 0.4 seconds. This response confirms that controller is working very well even if there exist some initial non zero value of yaw. It rapidly settles the QR at zero radian.

Above discussion confirms the validity of theoretical design of controller derived backstepping control strategy in previous chapter.

5.5.3 RESPONSE OF PITCH ANGLE

Next step in the simulations is to check the validity of controller designed to stabilization and tracking of pitch. Like last subsection 3 simulation responses will be obtained to demonstrate the performance of controller. A reference signal of 0.5 Radians is applied to the plant and response is noted. Following figure shows the response obtained.

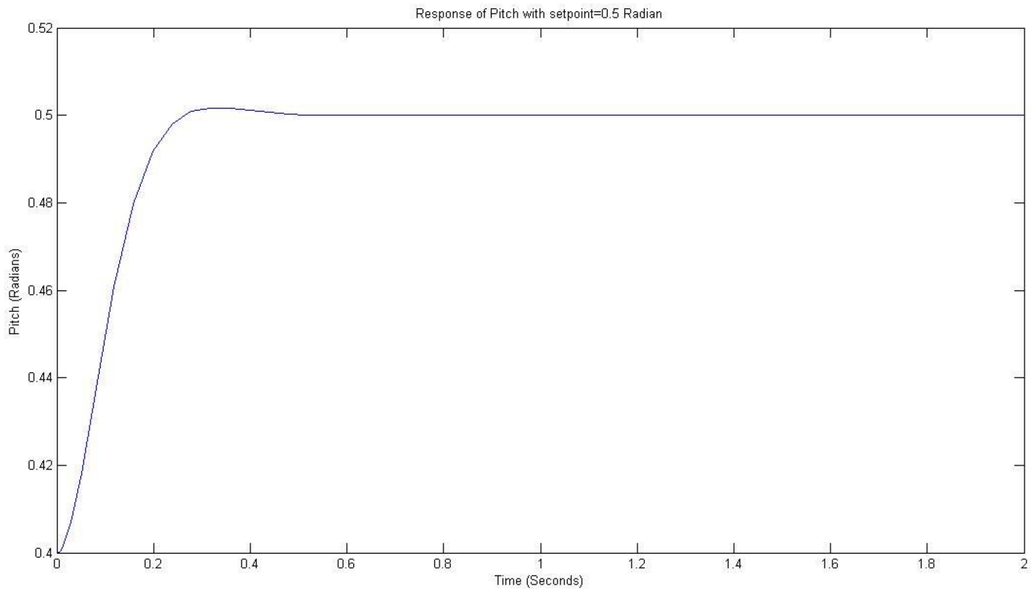

Figure 5-17 response of pitch with set point=0.5 Radian

From figure we obtain following response.

Offset error = 0

Percentage overshoot = 2%

Settling time = 0.3 seconds

It can be concluded that pitch can be controlled using the designed controller effectively.

Taking a response on 0.8 Rad reference signal, we get following result.

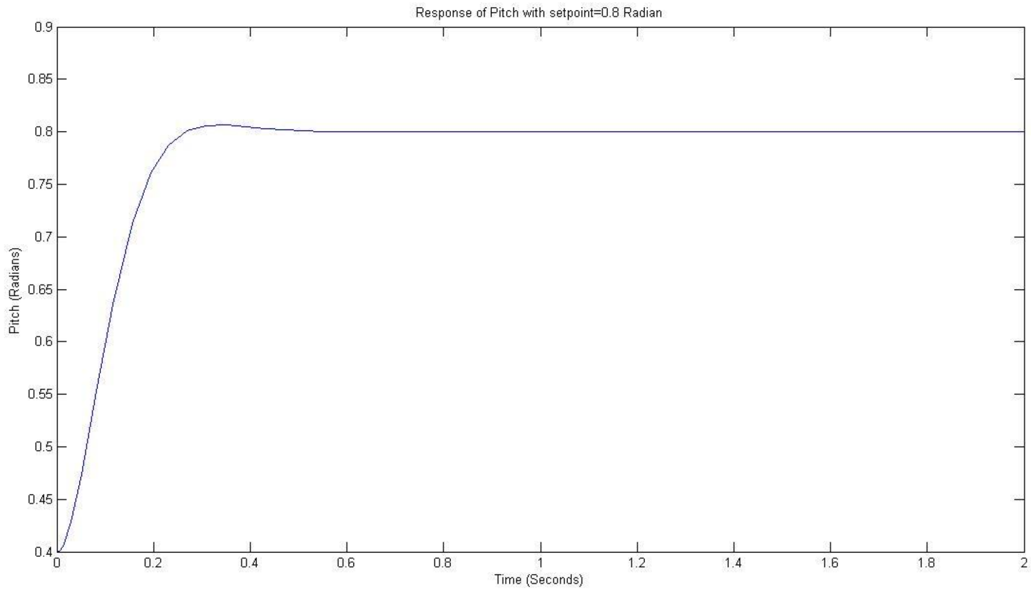

Figure 5-18 response of pitch with set point=0.8 Radian

From figure we obtain following response.

Offset error = 0

Percentage overshoot = 1.5%

Settling time = 2 seconds

Above figure shows that controller performance slightly decreases as there is some error till 2 seconds. However controller stabilizes the pitch efficiently.

Last simulation in this subsection is to set initial value to some nonzero value (0.4Radians here) and regulate it at 0 Radian. Figure 5-19 exhibits the simulation results.

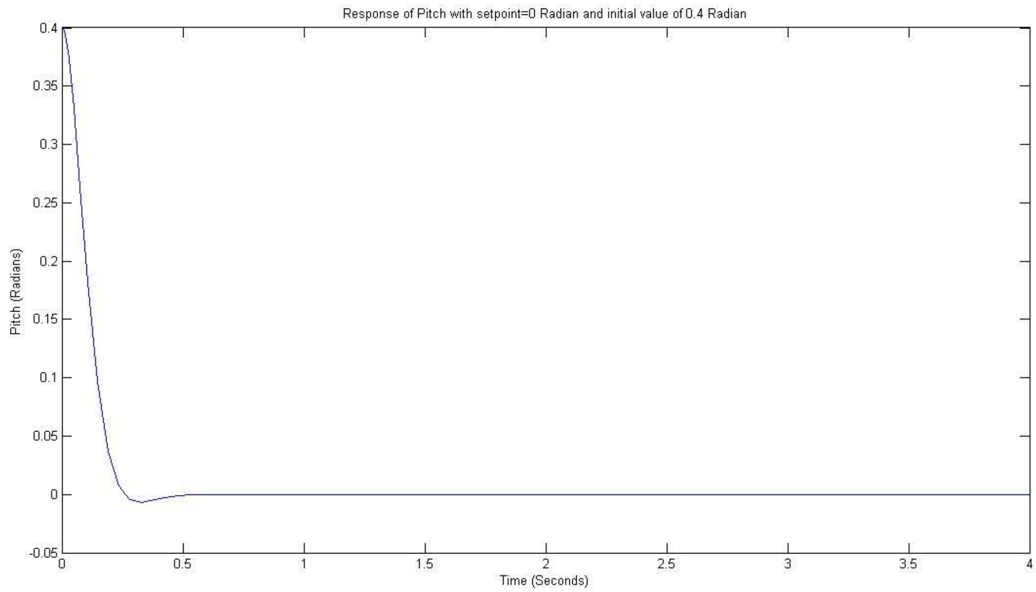

Figure 5-19 Pitch with set point=0 Radians with initial condition of 0.4 Rad

From figure we obtain following response.

Offset error = 0

Settling time = 2.6 seconds

Figures 5-17 to 5-19 confirm that controller designed for pitch has a very good response and it can be used to achieve stability under uncertainty.

5.5.4 RESPONSE OF ROLL ANGLE

Last simulation of this chapter is being done with roll controller. To demonstrate the effectiveness of controller responses are being taken on different set points and initial conditions. In Figure 5-20 roll response with set point 0.5 Rad is presented. Figure 5-21 gives the response with set point of 0.25 Rad and in figure 5-22 roll is to regulate at 0 Rad with an initial value of 0.25 Rad.

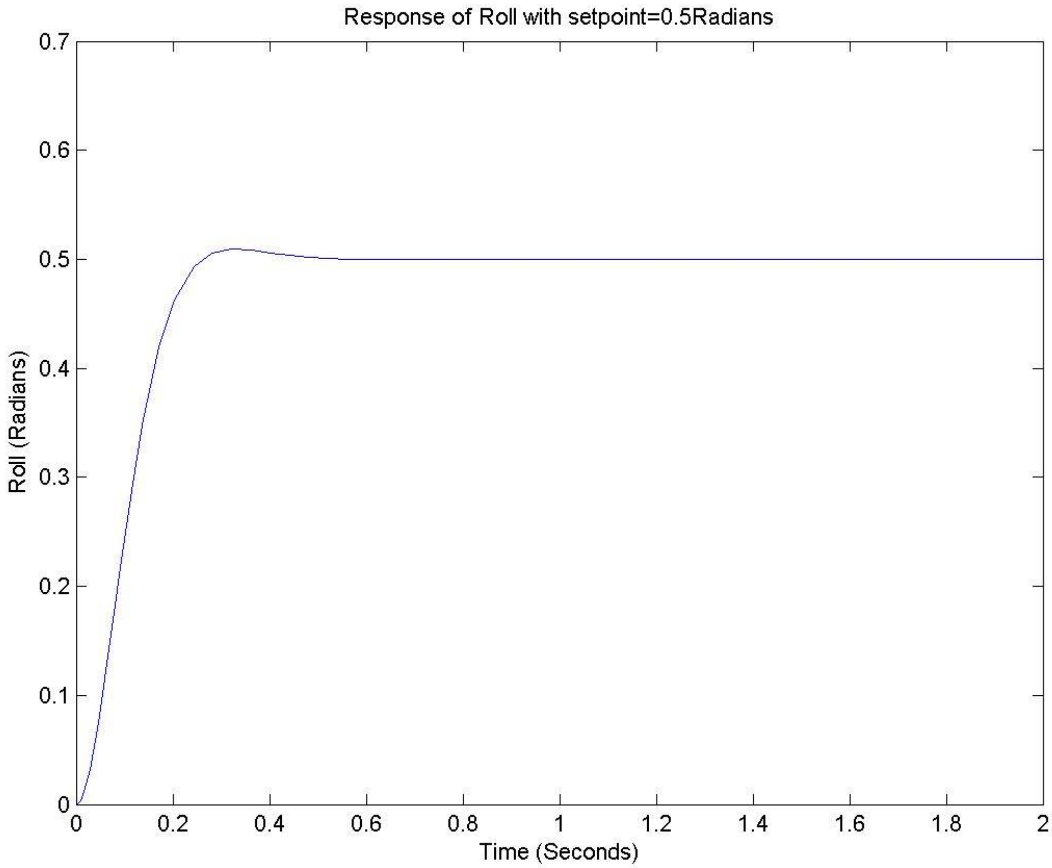

Figure 5-20 Roll with set point=0.5 Radians

From figure we obtain following response.

Offset error = 0

Percentage overshoot = 2%

Settling time = 0.25 seconds

Response validates the performance of designed controller.

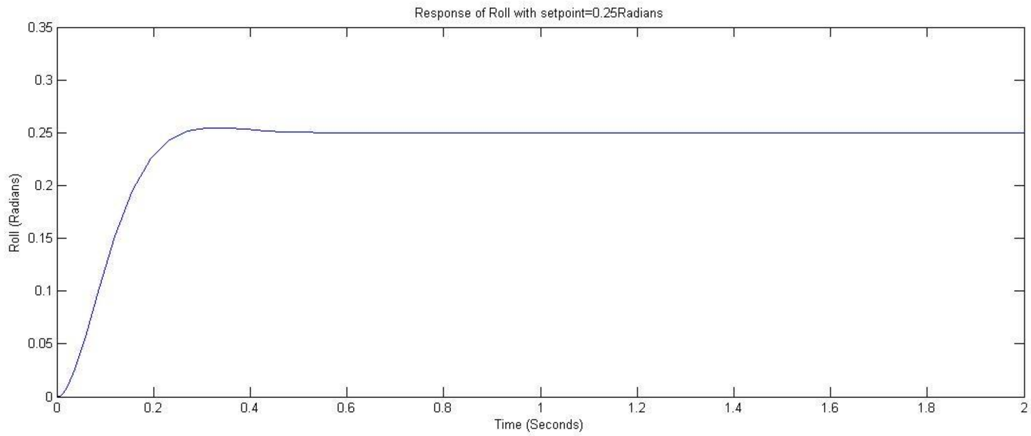

Figure 5-21 Roll with set point=0.25 Radians

From figure we obtain following response.

Offset error = 0

Percentage overshoot = 2%

Settling time = 0.32 seconds

Hence controller proves itself effective in controlling roll.

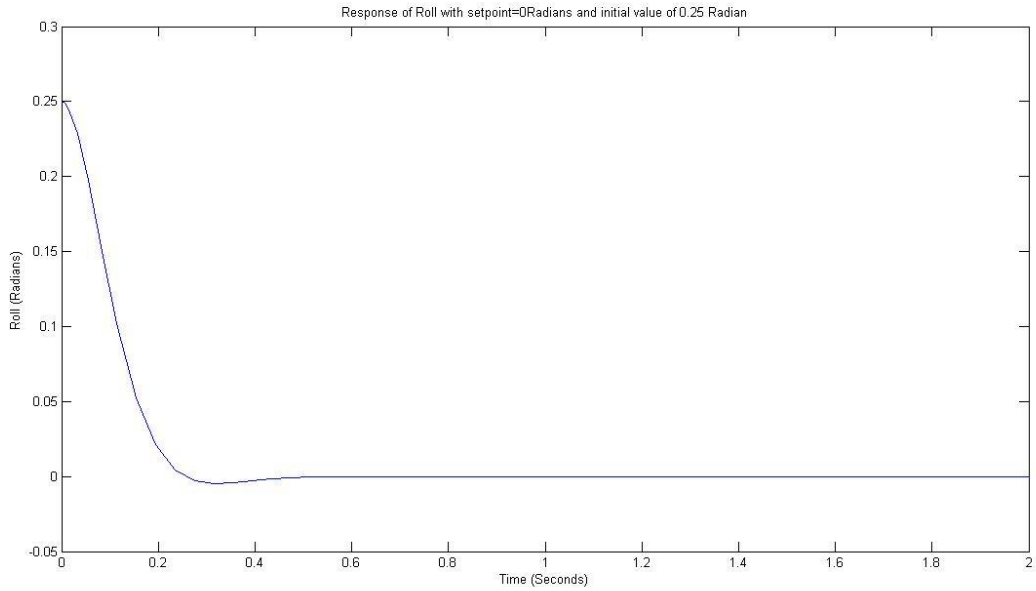

Figure 5-22 Roll with set point=0 Radians with initial condition of 0.3 Rad

Offset error = 0

Settling time = 0.32 seconds

All responses confirm the validity of theoretical design and it can be concluded that designed control has ability to stabilize Roll angle.

5.6 COMPARISON

In is section obtained results are compared with previous work. A paper [25] that uses PID controller and contains no uncertainty is chosen for comparison. Table 5-1 shows a comparison between two responses.

Table 5-1 Comparison

Position	Characteristic	Results obtained in this paper	Results obtained in [25]
Altitude	Settling time	0.6 seconds	0.3 seconds
	Overshoot	0	10%
Yaw	Settling time	0.5 seconds	0.15 seconds
	Overshoot	0	10%
Roll	Settling time	0.3 seconds	0.3 seconds
	Overshoot	3%	20%
Pitch	Settling time	0.4 seconds	0.3 seconds
	Overshoot	4%	20%

It can be seen easily that proposed controller causes less overshoot although it seems to take more settling time. But it should be noted that in [25] no uncertainty was included and in our simulations uncertainties are also included.

5.7 CONCLUSION

To demonstrate the validity of adaptive backstepping controllers, simulations are performed in this chapter. MATLAB SIMULINK package is used for simulation. Section 5.2 provides some overview about software. Open loop responses are given in section 5.3. SIMULINK model of quadrotor that was derived in chapter 4 is used here. Simulations show that QR is an unstable vehicle if used without compensator. In section 5.4 SIMULINK models of controllers derived in chapter 5 are presented. Most important part of this chapter is section 5.5. Controllers are connected with model of QR. Closed loop responses are taken with different set points and initial conditions. All responses affirm that designed adaptive controller has excellent response when used with QR UAV in uncertain situations.

CHAPTER

6 CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

In this thesis design of an adaptive backstepping controller for QR UAV is presented. Chapter 1 covers the basic information about QR. Chapter 3 deals with the system description and mathematical model of QR UAV. An adaptive backstepping controller for stabilizing and tracking of QR UAV is designed in chapter 4. According to designed requirement controller should be capable to handle uncertainties. Lyapunov stability theorem is used to prove the effectiveness of controller.

To validate the theoretical design simulations are performed in MATLAB. SIMULINK models of QR i.e. derived in chapter 4 and controllers designed in chapter 5 were used to get the response of QR UAV. In the first step open loop response was obtained which pointed out the instability of plant. Then QR was operated with designed controller and some initial condition to achieve some desired positions. Simulation results show that designed controller is very effective to control QR UAV even in case of model uncertainty.

Hence it can be concluded that in this thesis we are successful in designing an adaptive backstepping controller.

6.2 FUTURE WORK

It is a fact that nothing is perfect in this world. A lot of research has been done in this vast field and still there are many targets for researchers. Some proposals for future work are given below.

- Create a physical model and apply adaptive backstepping controller (designed in this thesis) on it to validate the results of this research.
  .
- Include a more accurate model involving parameter variations such as mass and inertia of quadrotor, model uncertainties and aerodynamic disturbances.
- Design a controller by combining sliding mode and adaptive controller and compare performance with the results of this controller

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