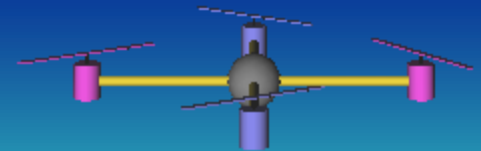


Nonlinear Control of Quadrotor

Nonlinear Analysis & Control Methods

503051621
K. OYTUN YAPICI



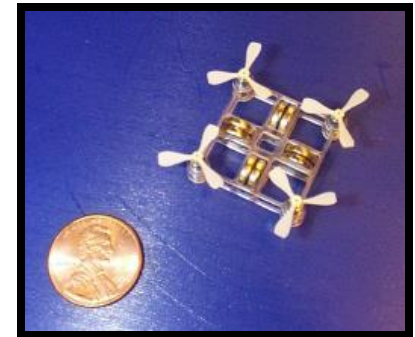
INTRODUCTION

Small-area monitoring, building exploration and intervention in hostile environments, surveillance, search and rescue in hazardous cluttered environments are the most important applications. Thus, vertical, stationary and slow flight capabilities seem to be unavoidable making the rotorcraft dynamic behavior a significant pro.

A quadrotor UAV can be highly maneuverable, has the potential to hover and to take off, fly, and land in small areas, and can have simple control mechanisms. However, because of its low rate damping, electronic stability augmentation is required for stable flight.

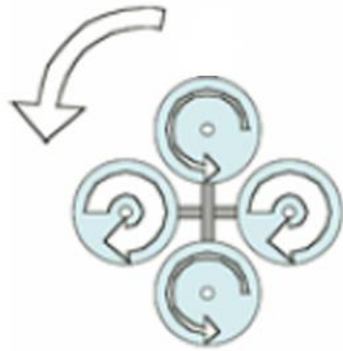
A quadrotor may also be able to fly closer to an obstacle than conventional helicopter configurations that have a large single rotor without fear of a rotor strike.

Typical aircraft can fly with considerably less thrust than required by a rotorcraft in hover. As the scale decreases, however, the ratio of wing lift to drag decreases and so does the conventional aircraft's advantage.

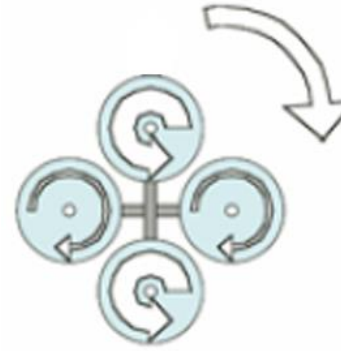


QUADROTOR CONCEPT

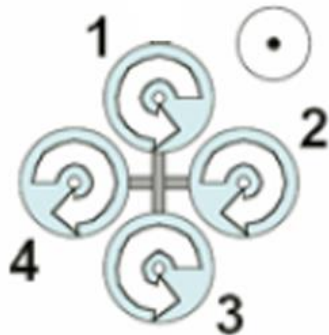
A quadrotor has four motors located at the front, rear, left, and right ends of a cross frame. The quadrotor is controlled by changing the speed of rotation of each motor. The front and rear rotors rotate in a counter-clockwise direction while the left and right rotors rotate in a clockwise direction to balance the torque created by the spinning rotors.



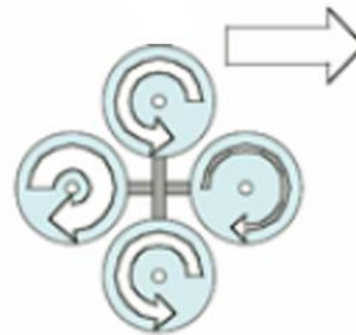
Rotate Left



Rotate Right



Going Up

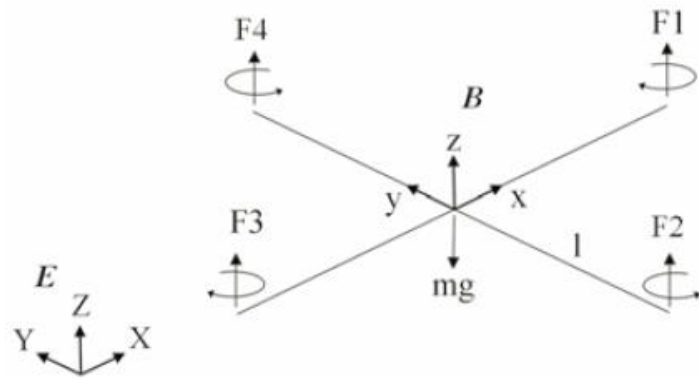


Move Right

MODELING ASSUMPTIONS

- The effects of the body moments on the translational dynamics are neglected.
- Gyroscopic effects are neglected.
- The ground effect is neglected.
- The blade flapping is not modeled.
- Motors are not modeled.
- The effects of air drag is neglected.
- The helicopter structure is supposed rigid.
- The helicopter structure is symmetric.
- The center of mass and the body fixed frame origin are assumed to coincide.

DYNAMIC MODEL



Newton-Euler formalism:

$$\begin{bmatrix} mI_{3 \times 3} & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \dot{V} \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} \omega \times mV \\ \omega \times I\omega \end{bmatrix} = \begin{bmatrix} F \\ \tau \end{bmatrix}$$

(Due to Assumptions)

Inertia Tensor:

$$I = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \rightarrow \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \quad (\text{Due to Symmetry})$$

Moment Vector:

$$\tau = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix}$$

Force Vector:

$$F = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}$$

Euler Angular Acc. Vector:

$$\dot{\omega} = \begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} = \begin{bmatrix} \ddot{\psi} \\ \ddot{\theta} \\ \ddot{\phi} \end{bmatrix}$$

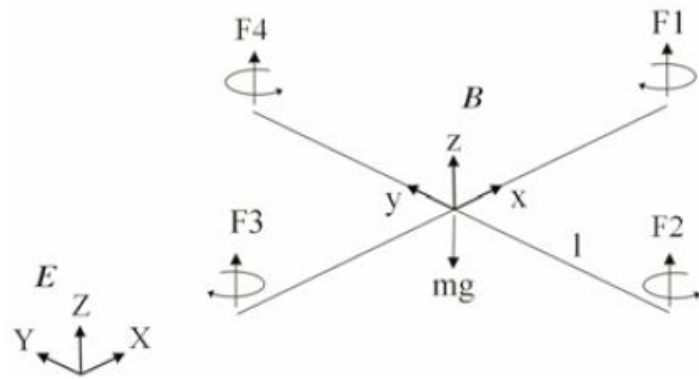
Identity Matrix:

$$I_{3 \times 3} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Acceleration Vector:

$$\dot{V} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix}$$

DYNAMIC MODEL



$$\begin{bmatrix} mI_{3 \times 3} & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \dot{V} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} F \\ \tau \end{bmatrix}$$

$$mI_{3 \times 3} \dot{V} = F$$

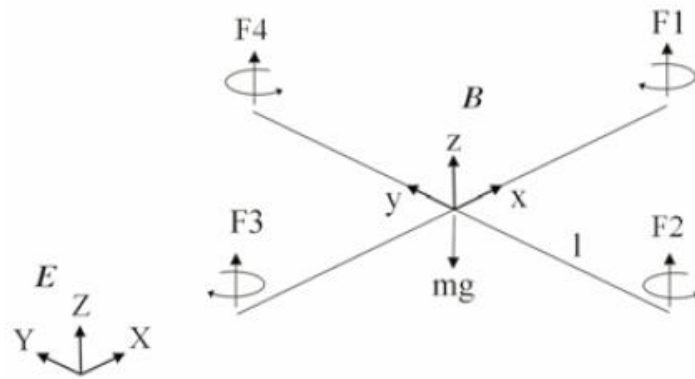
$$\begin{aligned} m\ddot{x} &= F_x & m\ddot{x} &= 0 \\ m\ddot{y} &= F_y & \rightarrow m\ddot{y} &= 0 \\ m\ddot{z} &= F_z & m\ddot{z} &= F_1 + F_2 + F_3 + F_4 \end{aligned}$$

$$I\dot{\omega} = \tau$$

$$\begin{aligned} I_{xx}\ddot{\psi} &= (F_4 - F_2)l \\ I_{yy}\ddot{\theta} &= (F_3 - F_1)l \\ I_{zz}\ddot{\phi} &= C(F_1 - F_2 + F_3 - F_4) \end{aligned}$$

C: Force to Moment Scaling Factor

DYNAMIC MODEL

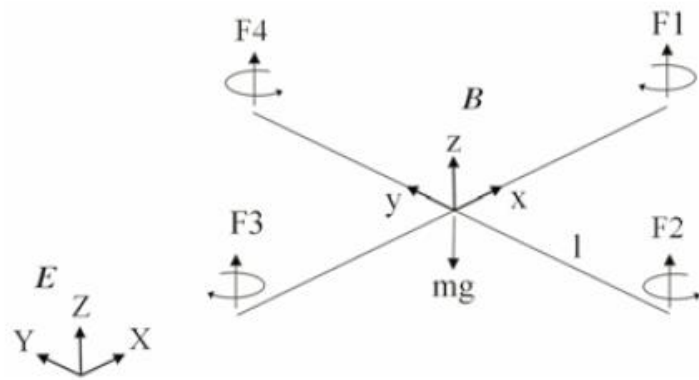


- Rotation of ψ around x axis : **roll**
- Rotation of θ around y axis : **pitch**
- Rotation of ϕ around z axis : **yaw**

$${}^E_B R_{zyx}(\phi, \psi, \theta) = R_z(\phi)R_y(\theta)R_x(\psi) = \begin{bmatrix} \cos \phi & -\sin \phi & 0 \\ \sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \psi & -\sin \psi \\ 0 & \sin \psi & \cos \psi \end{bmatrix}$$

$${}^E_B R_{zyx}(\phi, \theta, \psi) = \begin{bmatrix} \cos \phi \cos \theta & \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi & \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi \\ \sin \phi \cos \theta & \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & \sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi \\ -\sin \theta & \cos \theta \sin \psi & \cos \theta \cos \psi \end{bmatrix}$$

DYNAMIC MODEL

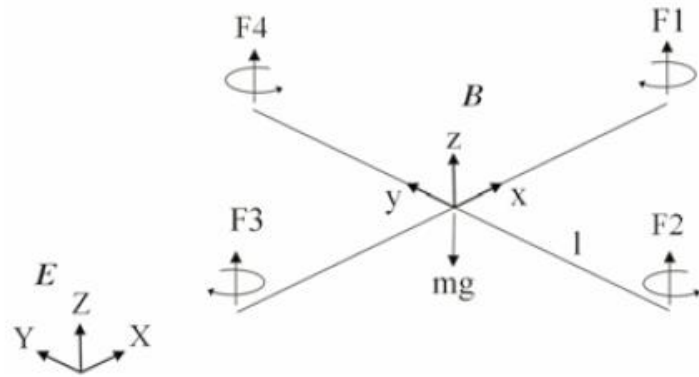


$${}^E R_{zyx}(\phi, \theta, \psi) = \begin{bmatrix} c\phi c\theta & c\phi s\theta s\psi - s\phi c\psi & c\phi s\theta c\psi + s\phi s\psi \\ s\phi c\theta & s\phi s\theta s\psi + c\phi c\psi & s\phi s\theta c\psi - c\phi s\psi \\ -s\theta & c\theta s\psi & c\theta c\psi \end{bmatrix}$$

$$R \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = R \begin{bmatrix} 0 \\ 0 \\ F_1 + F_2 + F_3 + F_4 \end{bmatrix}$$

$$\begin{aligned} m\ddot{X} &= \sum_{n=1}^4 F_i (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi) \\ m\ddot{Y} &= \sum_{n=1}^4 F_i (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi) \\ m\ddot{Z} &= \sum_{n=1}^4 F_i (\cos \theta \cos \psi) - mg \end{aligned}$$

DYNAMIC MODEL

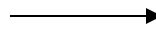


$$u_1 = (F_1 + F_2 + F_3 + F_4) / m$$

$$u_2 = (F_4 - F_2) / I_{yy}$$

$$u_3 = (F_3 - F_1) / I_{xx}$$

$$u_4 = C(F_1 - F_2 + F_4 - F_3) / I_{zz}$$



$$m\ddot{X} = \sum_{i=1}^n F_i (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)$$

$$m\ddot{Y} = \sum_{i=1}^n F_i (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi)$$

$$m\ddot{Z} = \sum_{i=1}^n F_i (\cos \theta \cos \psi) - mg$$

$$I_{xx}\ddot{\psi} = (F_3 - F_1)l$$

$$I_{yy}\ddot{\theta} = (F_4 - F_2)l$$

$$I_{zz}\ddot{\phi} = C(F_1 - F_2 + F_3 - F_4)$$

$$\ddot{X} = u_1 (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)$$

$$\ddot{Y} = u_1 (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi)$$

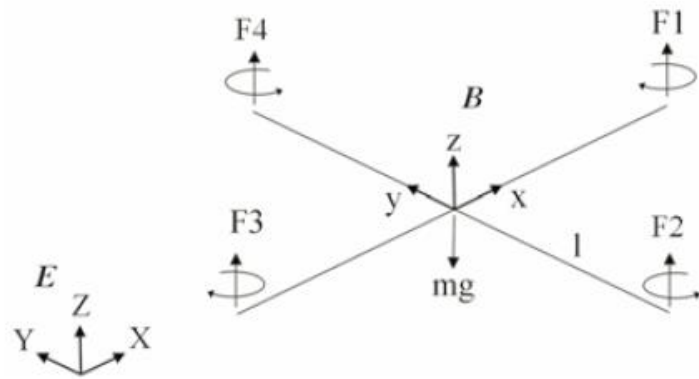
$$\ddot{Z} = u_1 (\cos \theta \cos \psi) - g$$

$$\ddot{\theta} = u_2 l$$

$$\ddot{\psi} = u_3 l$$

$$\ddot{\phi} = u_4$$

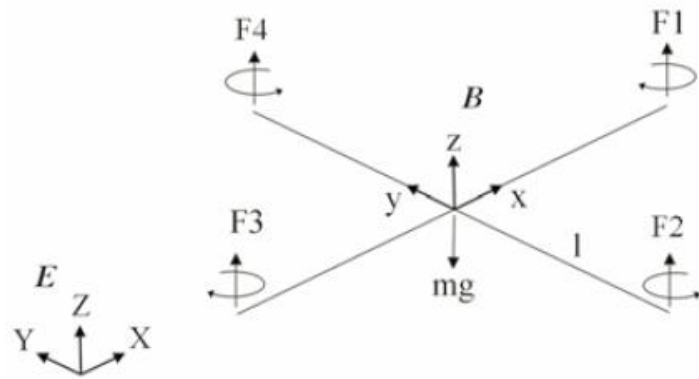
DYNAMIC MODEL



Euler angular rates differs from body angular rates:

$$\begin{bmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 1 & \sin \psi \tan \theta & \cos \psi \tan \theta \\ 0 & \cos \psi & -\sin \psi \\ 0 & \sin \psi / \cos \theta & \cos \psi / \cos \theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

PHYSICAL VALUES & CONSTRAINTS



Physical Values:

$$l = 0.21m$$

$$I_{xx} = 0.0142 \text{ kg.m}^2$$

$$I_{yy} = 0.0142 \text{ kg.m}^2$$

$$I_{zz} = 0.0071 \text{ kg.m}^2$$

$$m = 0.56 \text{ kg}$$

$$g = 9.81 \text{ m/s}^2$$

$$C = 1.3$$

Constraints:

$$F_{\max} = 10 \text{ N}$$

$$0 < u_1 \leq 4F_{\max} / m$$

$$-2F_{\max} / l \leq u_2 \leq 2F_{\max} / l$$

$$-2F_{\max} / l \leq u_3 \leq 2F_{\max} / l$$

$$-2CF_{\max} \leq u_4 \leq 2CF_{\max}$$

To avoid crash

$$4F_{\max} \cos \theta \cos \psi \geq mg$$

is required.

PROPERTIES OF DYNAMIC MODEL

$$\ddot{X} = u_1 (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)$$

$$\ddot{Y} = u_1 (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi)$$

$$\ddot{Z} = u_1 (\cos \theta \cos \psi) - g$$

$$\ddot{\theta} = u_2 l$$

$$\ddot{\psi} = u_3 l$$

$$\ddot{\phi} = u_4$$

- Rotations are not affected by translations.
- Angular subsystem is linear.
- System is underactuated.
- System has coupling effects.
- System is unstable.

ALTITUDE & ANGULAR ROTATIONS CONTROL

$$\ddot{X} = u_1 (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)$$

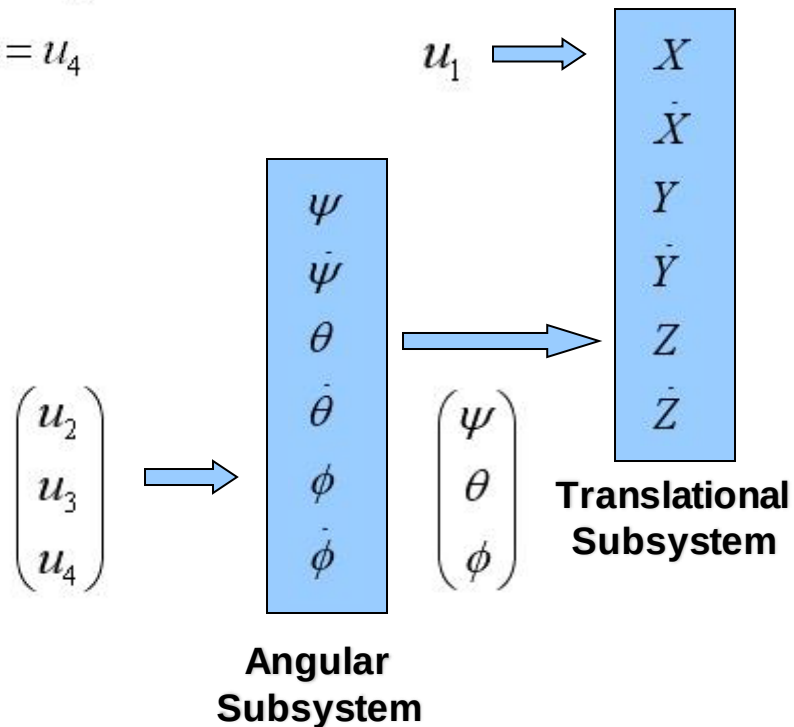
$$\ddot{Y} = u_1 (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi)$$

$$\ddot{Z} = u_1 (\cos \theta \cos \psi) - g$$

$$\ddot{\theta} = u_2 l$$

$$\ddot{\psi} = u_3 l$$

$$\ddot{\phi} = u_4$$



System States:

$$x_1 = X$$

$$x_2 = \dot{x}_1 = \dot{X}$$

$$x_3 = Y$$

$$x_4 = \dot{x}_3 = \dot{Y}$$

$$x_5 = Z$$

$$x_6 = \dot{x}_5 = \dot{Z}$$

$$x_7 = \theta$$

$$x_8 = \dot{x}_7 = \dot{\theta}$$

$$x_9 = \psi$$

$$x_{10} = \dot{x}_9 = \dot{\psi}$$

$$x_{11} = \phi$$

$$x_{12} = \dot{\phi}$$

CONTROL OF ANGULAR SUBSYSTEM

Desired states:

$$X_{\alpha}^d = (x_7^d, 0, x_9^d, 0, x_{11}^d, 0)^T$$

If we consider a Lyapunov function as:

$$V = \frac{(x_7 - x_7^d)^2 + x_8^2 + (x_9 - x_9^d)^2 + x_{10}^2 + (x_{11} - x_{11}^d)^2 + x_{12}^2}{2}$$

Positive defined around the desired position X_{α}^d

$$\dot{V} = (x_7 - x_7^d)\dot{x}_7 + x_8\dot{x}_8 + (x_9 - x_9^d)\dot{x}_9 + x_{10}\dot{x}_{10} + (x_{11} - x_{11}^d)\dot{x}_{11} + x_{12}\dot{x}_{12}$$

Substituting equalities at the right we get:

$$\dot{V} = (x_7 - x_7^d)x_8 + x_8u_2l + (x_9 - x_9^d)x_{10} + x_{10}u_3l + (x_{11} - x_{11}^d)x_{12} + x_{12}u_4$$

$$x_7 = \theta$$

$$x_8 = \dot{x}_7 = \dot{\theta}$$

$$\dot{x}_8 = u_2l$$

$$x_9 = \psi$$

$$x_{10} = \dot{x}_9 = \dot{\psi}$$

$$\dot{x}_{10} = u_3l$$

$$x_{11} = \phi$$

$$x_{12} = \dot{\phi}$$

$$\dot{x}_{12} = u_4$$

CONTROL OF ANGULAR SUBSYSTEM

$$\dot{V} = (x_7 - x_7^d)x_8 + x_8u_2l + (x_9 - x_9^d)x_{10} + x_{10}u_3l + (x_{11} - x_{11}^d)x_{12} + x_{12}u_4 \quad x_7 = \theta$$

If we choose control laws as:

$$u_2 = -\frac{1}{l}(x_7 - x_7^d) - k_1x_8$$

$$u_3 = -\frac{1}{l}(x_9 - x_9^d) - k_2x_{10}$$

$$u_4 = -(x_{11} - x_{11}^d) - k_3x_{12}$$

we get:

$$\dot{V} = -k_1lx_8^2 - k_2lx_{10}^2 - k_3x_{12}^2$$

for $k_1, k_2, k_3 > 0$, $\dot{V}$ will be negative semi-definite thus

the equilibrium point X_α^d is stable.

By applying La Salle theorem we see that the maximum invariance set of angular subsystem under control contained in the set $\dot{V} = 0$ is restricted to the equilibrium point. Thus, subsystem is asymptotically stable.

As $\|X_\alpha\| \rightarrow \infty$ $V(X_\alpha) = \infty$ subsystem is globally stable.

$$x_8 = \dot{x}_7 = \dot{\theta}$$

$$\dot{x}_8 = u_2l$$

$$x_9 = \psi$$

$$x_{10} = \dot{x}_9 = \dot{\psi}$$

$$\dot{x}_{10} = u_3l$$

$$x_{11} = \phi$$

$$x_{12} = \dot{\phi}$$

$$\dot{x}_{12} = u_4$$

ALTITUDE CONTROLLER

To control altitude we can apply feedback linearization to $\ddot{Z}$

$$\ddot{Z} = u_1 (\cos \theta \cos \psi) - g$$

Selecting control law to cancel nonlinearities we get:

$$u_1 = \frac{v_1 + g}{\cos \theta \cos \psi}$$

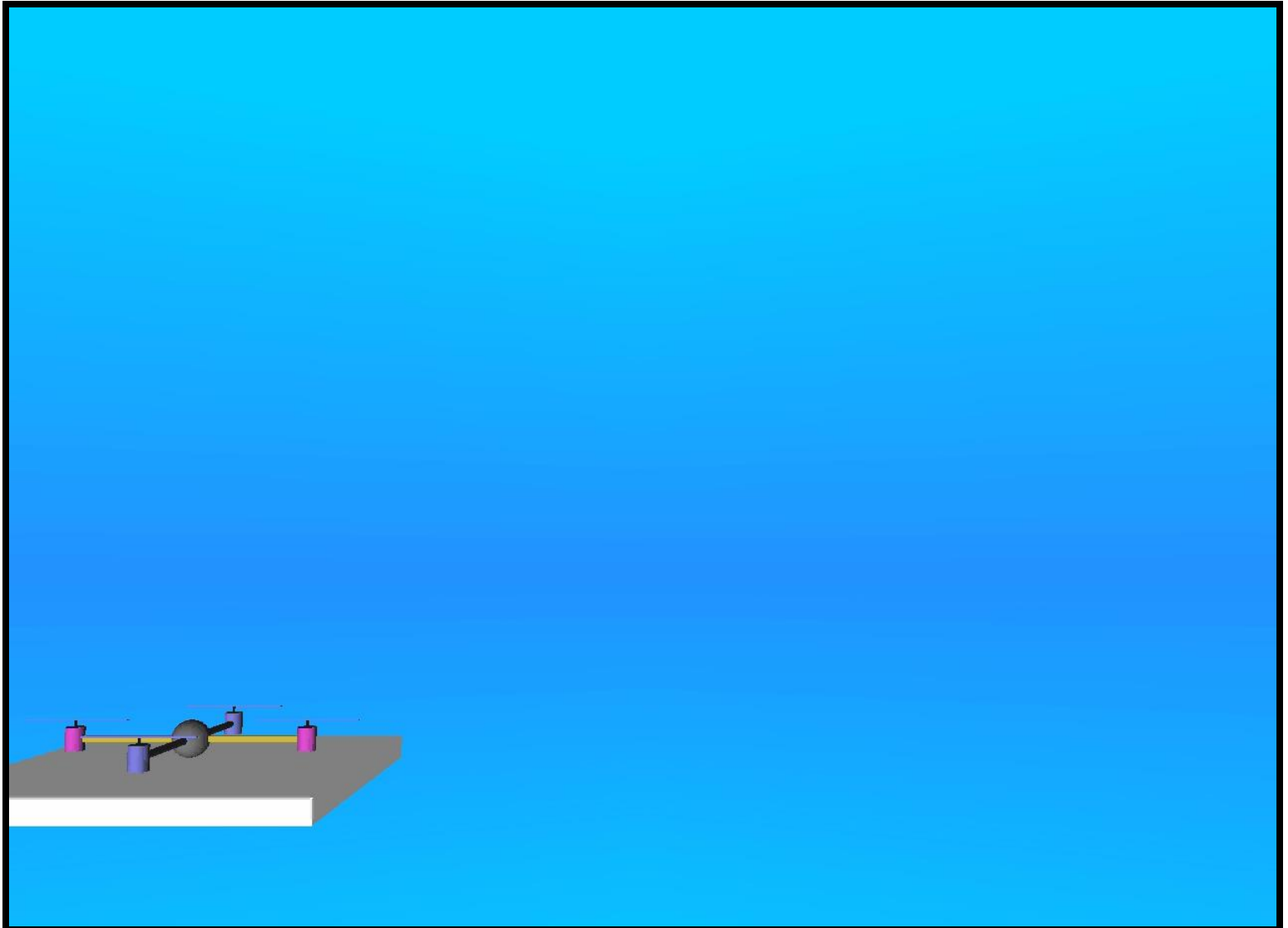
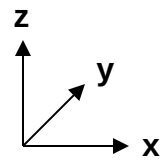
Selecting v_1 as a PD controller:

$$v_1 = k_d (\dot{Z}_d - \dot{Z}) + k_p (Z_d - Z)$$

We can exponentially stabilize the height.

$$Z_0 = 5m \quad \theta_0 = \pi/8 \quad \psi_0 = \pi/10 \quad \phi_0 = \pi/4 \quad k_1, k_2, k_3 = 4$$

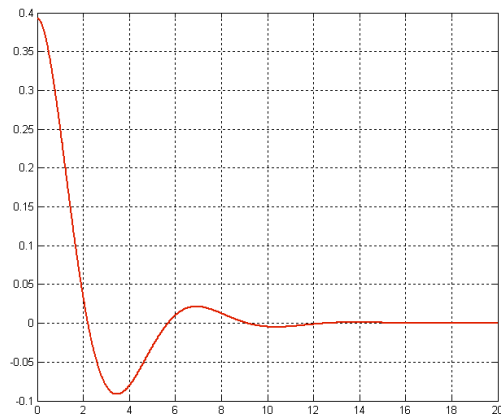
$$Z_d = 0m \quad \theta_d = 0 \quad \psi_d = 0 \quad \phi_d = 0$$



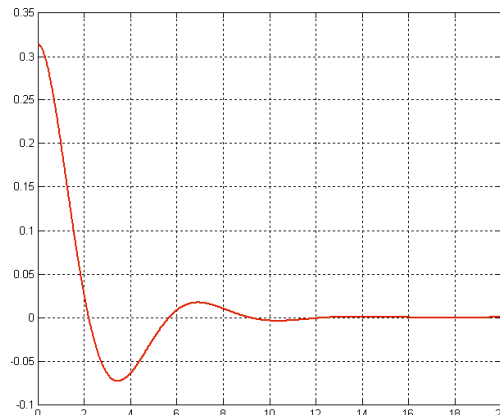
$$Z_0 = 5m \quad \theta_0 = \pi/8 \quad \psi_0 = \pi/10 \quad \phi_0 = \pi/4 \quad k_1, k_2, k_3 = 4$$

$$Z_d = 0m \quad \theta_d = 0 \quad \psi_d = 0 \quad \phi_d = 0$$

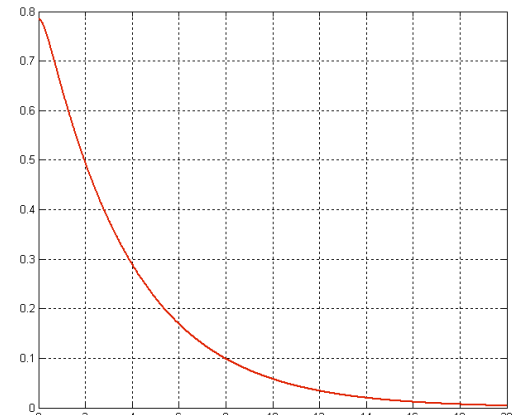
Pitch (θ)



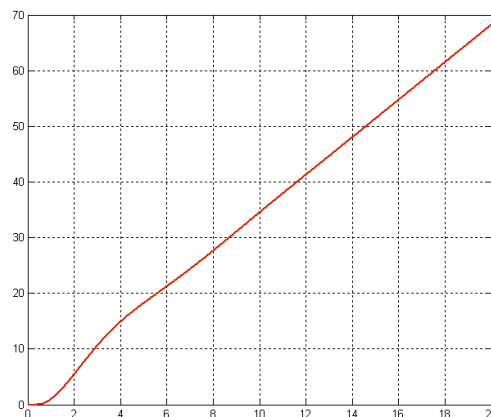
Roll (ψ)



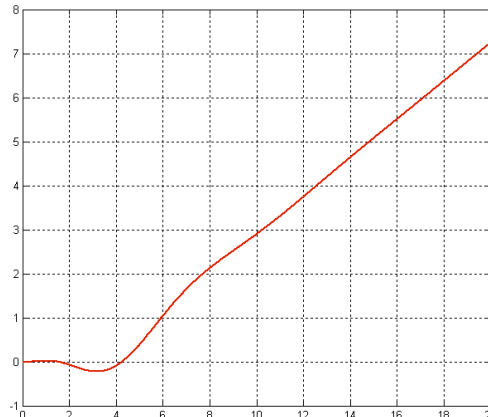
Yaw (Φ)



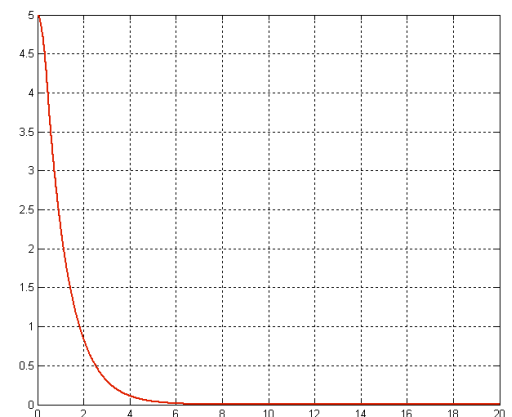
X



Y

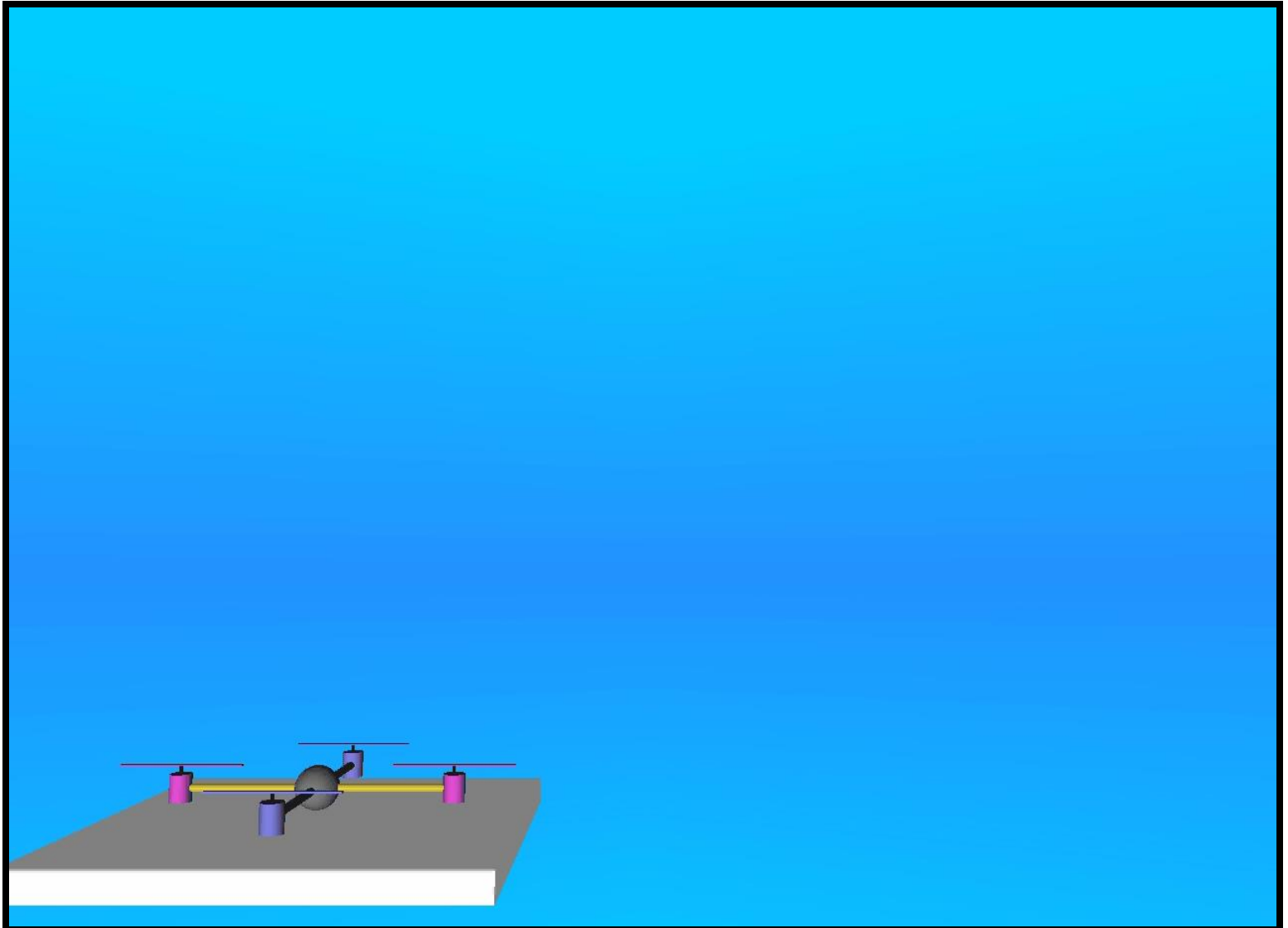
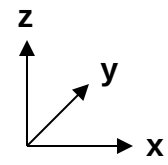


Z



$$Z_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 2m \quad \theta_d = \pi / 6$$



X MOTION CONTROL

We can apply feedback linearization through θ :

$$\ddot{X} = u_1 (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)$$

After linearization we will get:

$$\ddot{X} = v_1$$

$$v_1 = K_d (\dot{X}_d - \dot{X}) + K_p (X_d - X)$$

So we can derive θ_d from following equation:

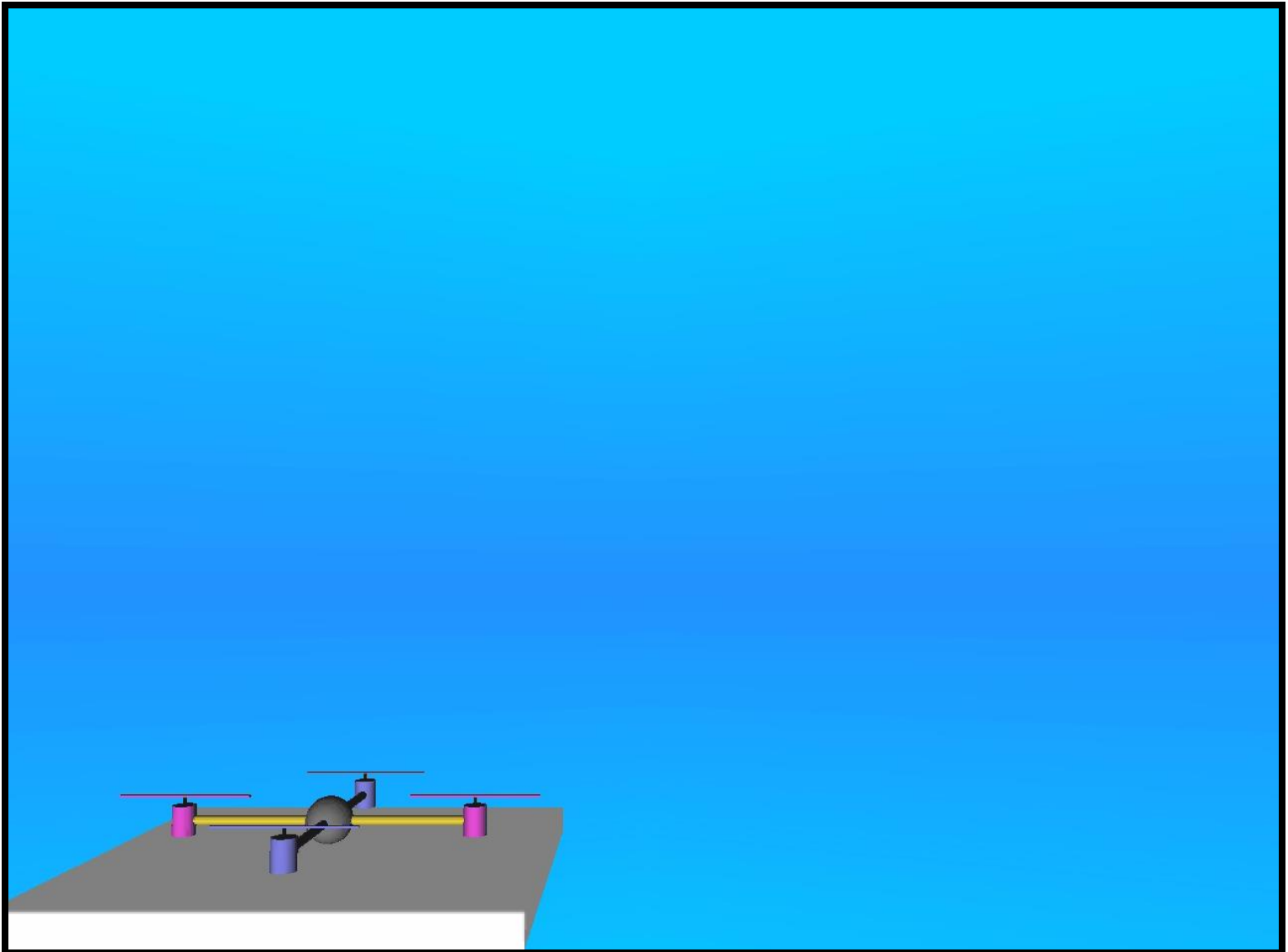
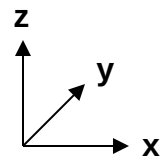
$$\ddot{X} = K_d (\dot{X}_d - \dot{X}) + K_p (X_d - X) = u_1 (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)$$

Assuming $\phi = 0$, $\psi = 0$ for simplicity we get:

$$\theta_d = \arcsin \left(\frac{K_d (\dot{X}_d - \dot{X}) + K_p (X_d - X)}{u_1} \right)$$

$$Z_0 = 0m \quad X_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

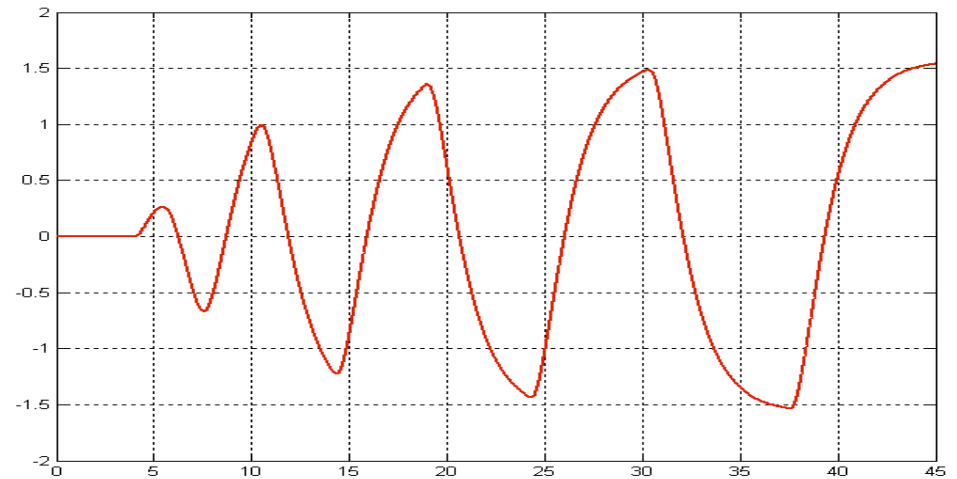
$$Z_d = 2m \quad X_d = 4m$$



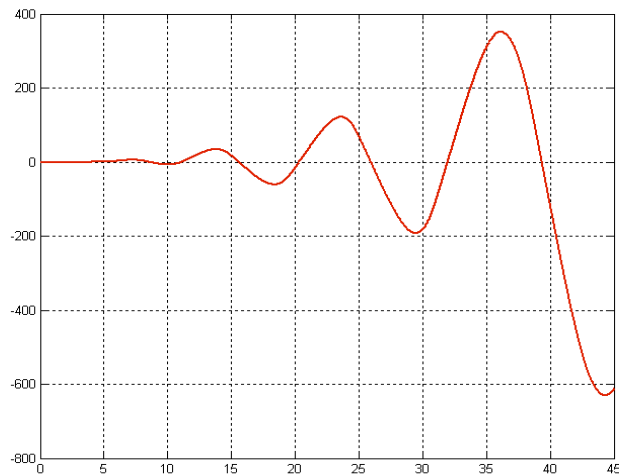
$$Z_0 = 0m \quad X_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 2m \quad X_d = 4m$$

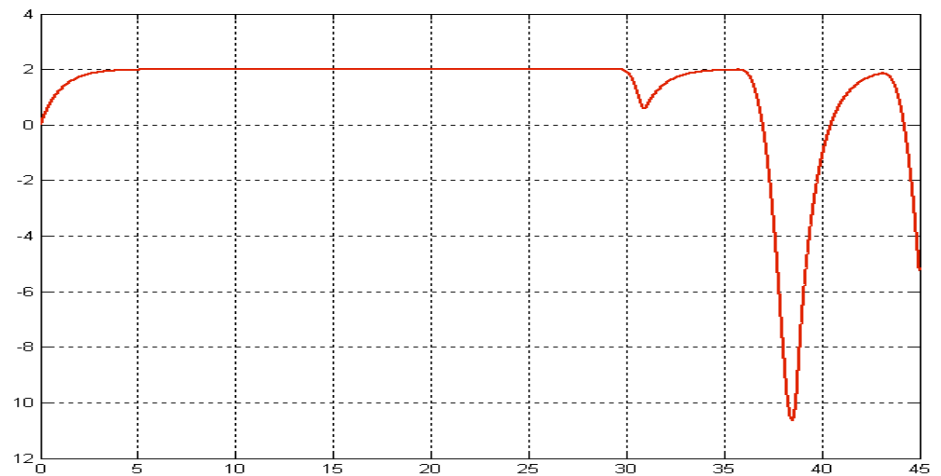
Pitch (θ)



X



Z



QUADROTOR CONTROL

ANGULAR SUBSYSTEM

$$\begin{aligned}\ddot{\theta} &= u_2 l & \ddot{\theta} &= K_d(\dot{\theta}_d - \dot{\theta}) + K_p(\theta_d - \theta) \\ \ddot{\psi} &= u_3 l & \Rightarrow \ddot{\psi} &= K_d(\dot{\psi}_d - \dot{\psi}) + K_p(\psi_d - \psi) \\ \ddot{\phi} &= u_4 & \ddot{\phi} &= K_d(\dot{\phi}_d - \dot{\phi}) + K_p(\phi_d - \phi)\end{aligned}$$

TRANSLATIONAL SUBSYSTEM

Z Motion:

$$\ddot{Z} = u_1(\cos \theta \cos \psi) - g$$

$$u_1 = \frac{v_1 + g}{\cos \theta \cos \psi}$$

$$v_1 = k_d(\dot{Z}_d - \dot{Z}) + k_p(Z_d - Z)$$

QUADROTOR CONTROL

TRANSLATIONAL SUBSYSTEM

X, Y Motion:

$$\ddot{X} = u_1 (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi) \quad \theta \rightarrow X$$

$$\ddot{Y} = u_1 (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi) \quad \psi \rightarrow Y$$

Assuming $\phi = 0$:

$$\ddot{X} = u_1 (\sin \theta \cos \psi)$$

$$\ddot{Y} = u_1 (\sin \psi)$$

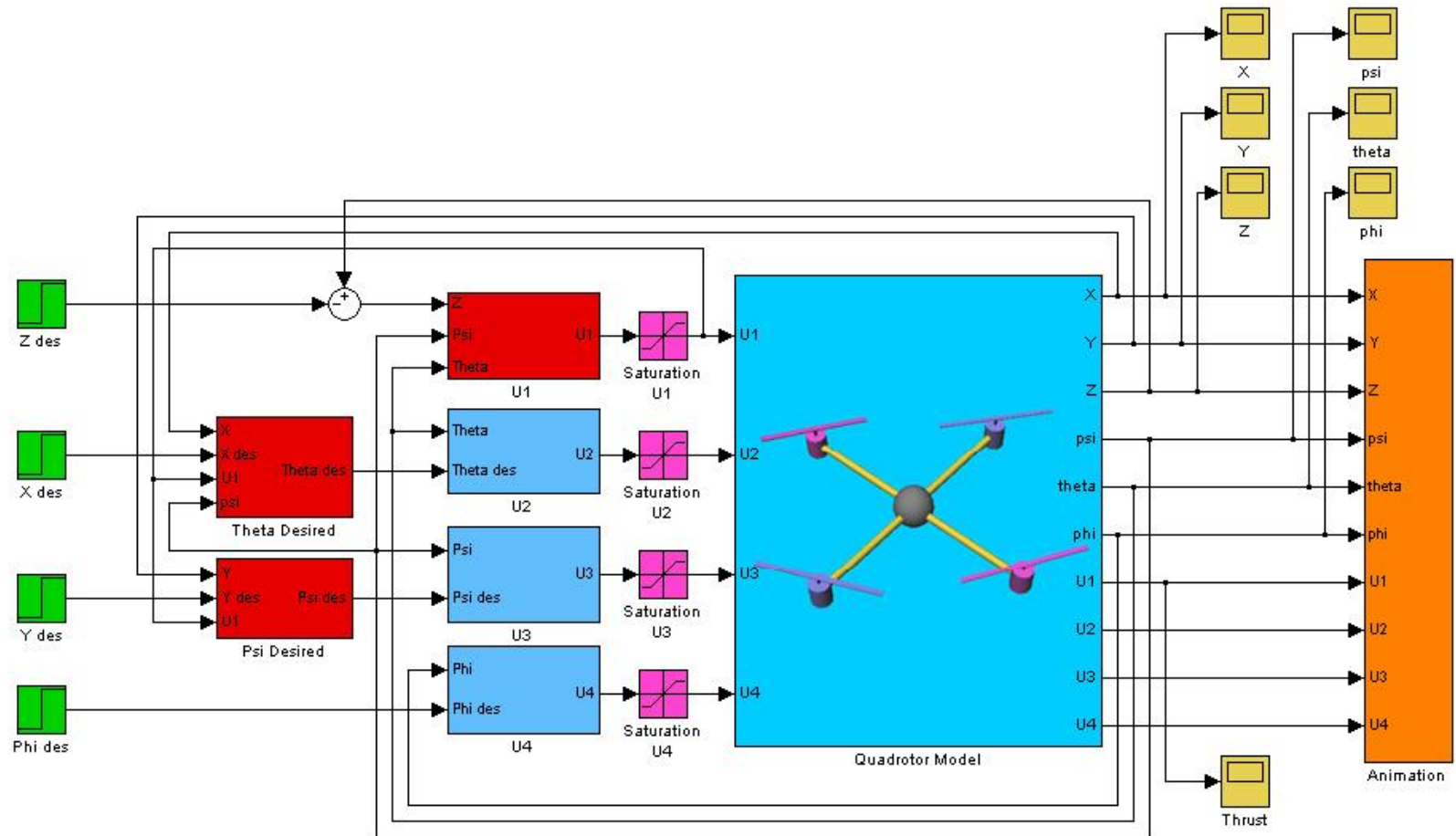
Thus we get:

$$\ddot{X} = K_d (\dot{X}_d - \dot{X}) + K_p (X_d - X) = u_1 (\sin \theta \cos \psi)$$

$$\ddot{Y} = K_d (\dot{Y}_d - \dot{Y}) + K_p (Y_d - Y) = u_1 (\sin \psi)$$

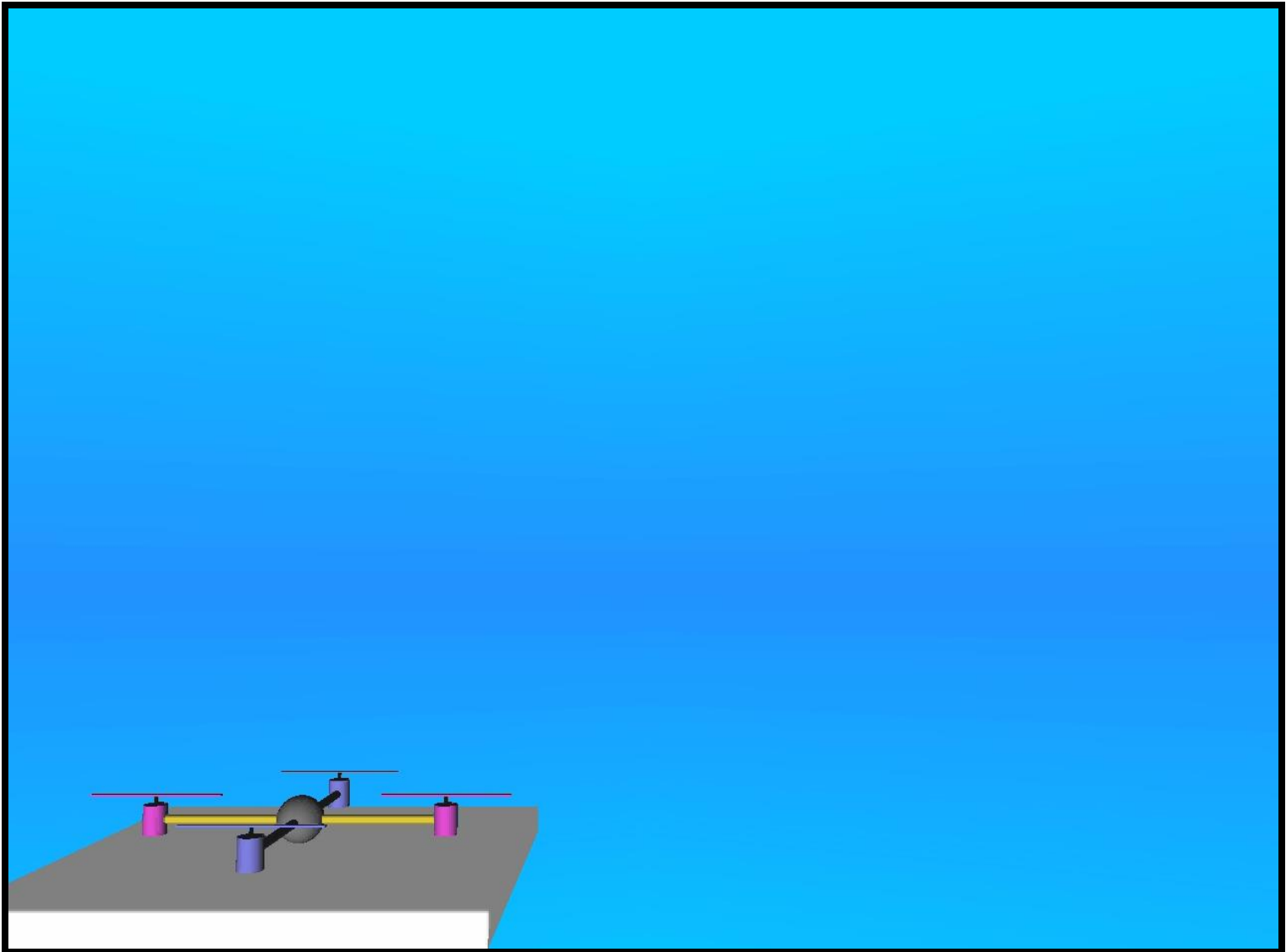
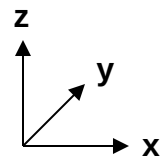
$$\theta_d = \arcsin \left(\frac{K_d (\dot{X}_d - \dot{X}) + K_p (X_d - X)}{u_1 \cos \psi} \right) \quad \psi_d = \arcsin \left(\frac{K_d (\dot{Y}_d - \dot{Y}) + K_p (Y_d - Y)}{u_1} \right)$$

SIMULINK BLOCK DIAGRAM



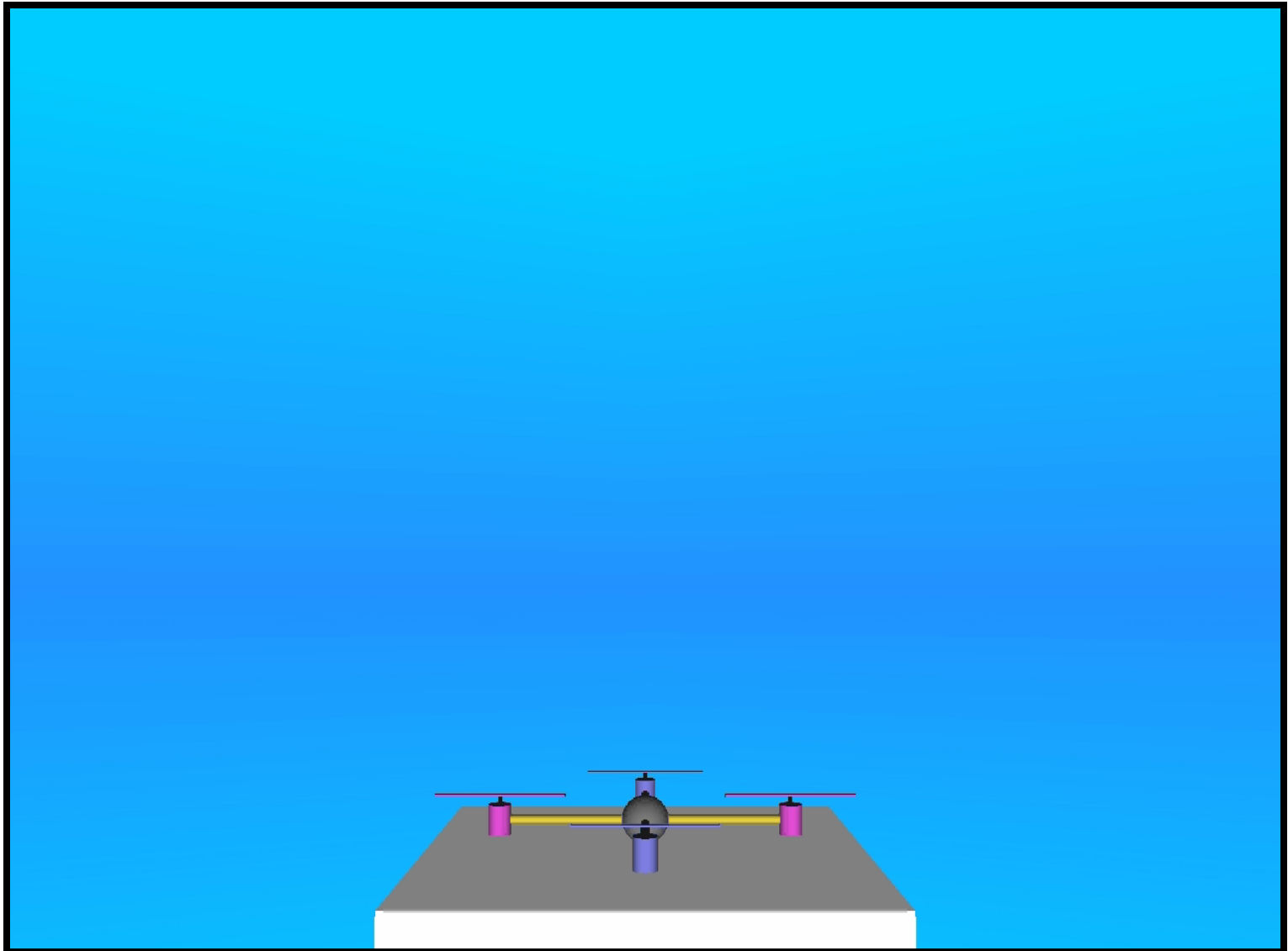
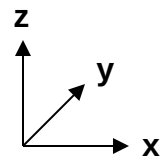
$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 2m \quad X_d = 4m$$



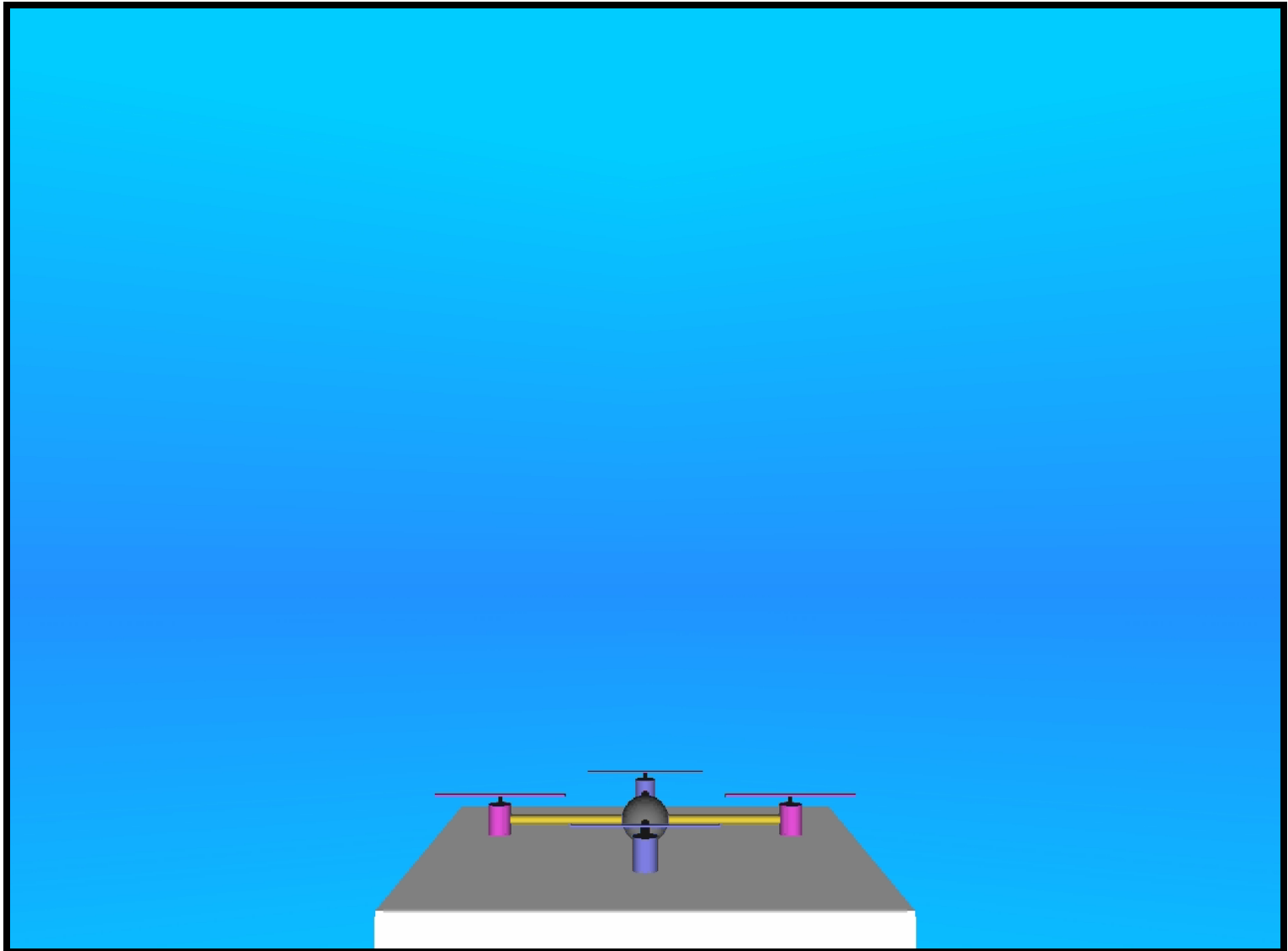
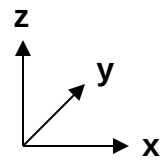
$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 2m \quad Y_d = -4m$$



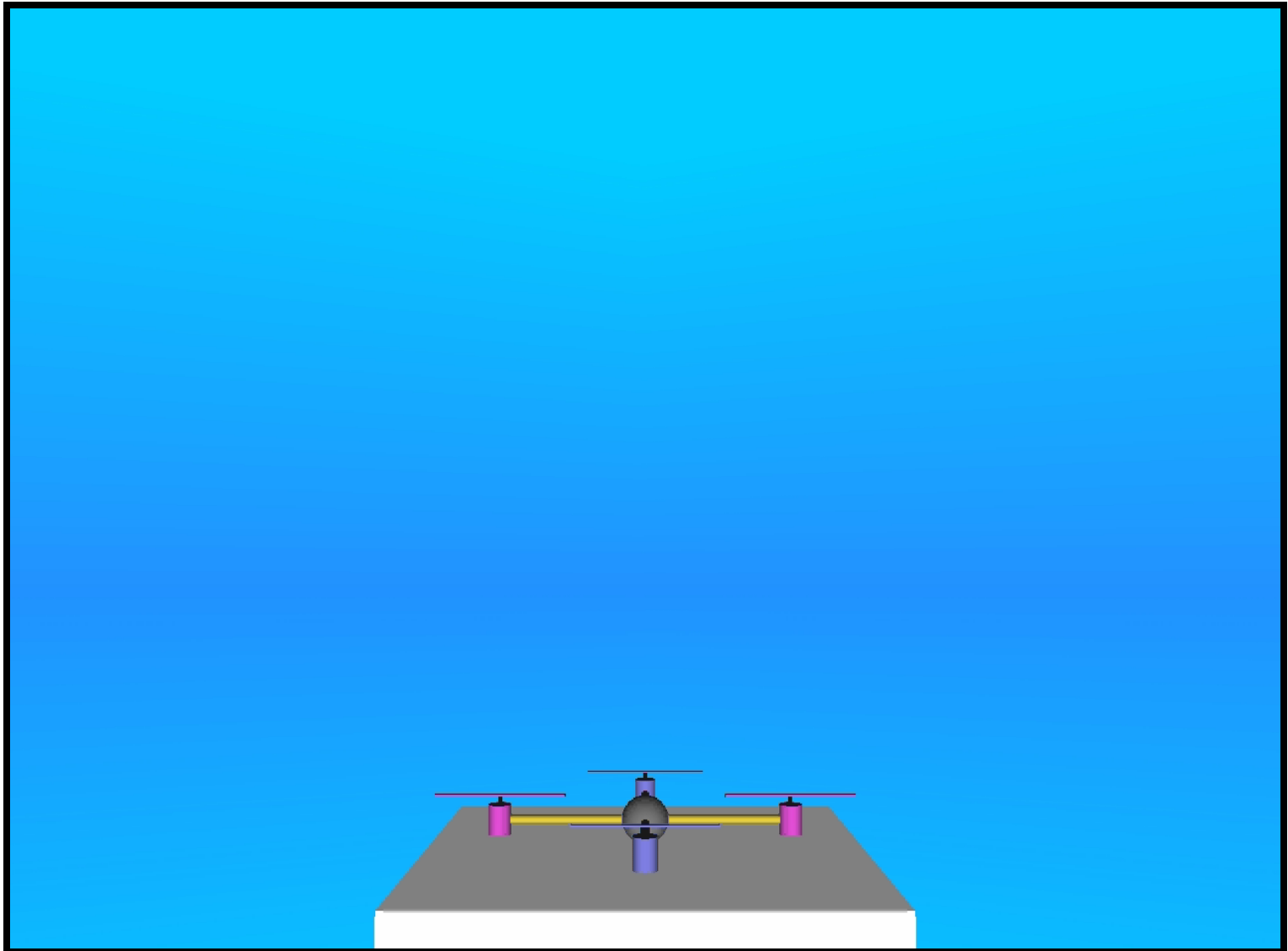
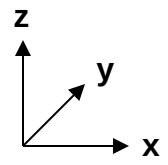
$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 2m \quad X_d = 4m \quad Y_d = -4m$$



$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

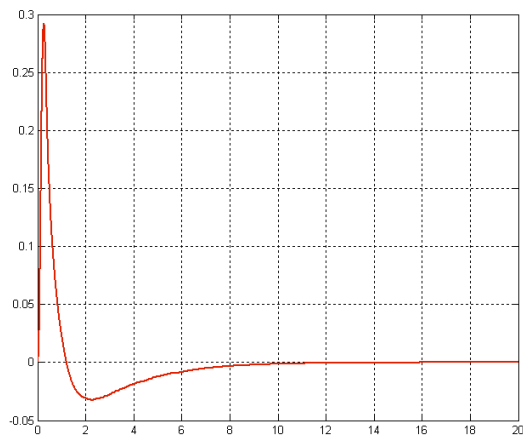
$$Z_d = 2m \quad X_d = 4m \quad Y_d = -4m$$



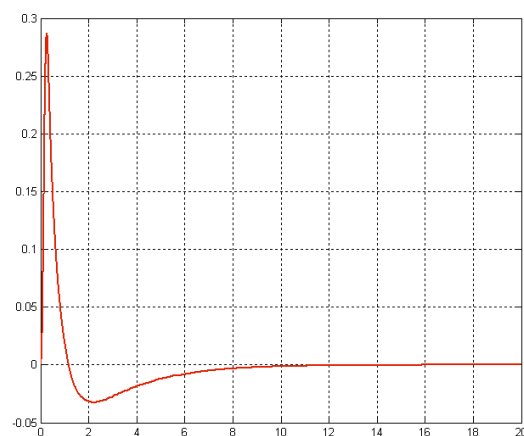
$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 2m \quad X_d = 4m \quad Y_d = -4m$$

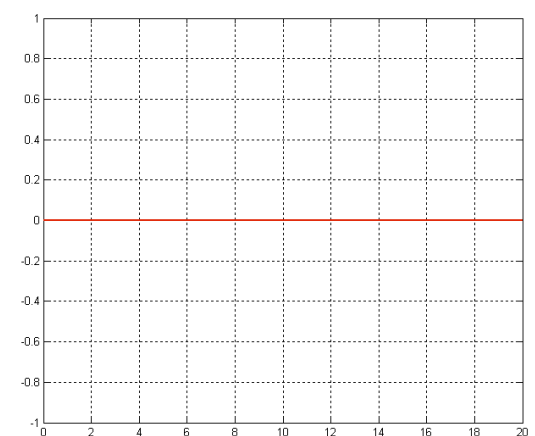
Pitch (θ)



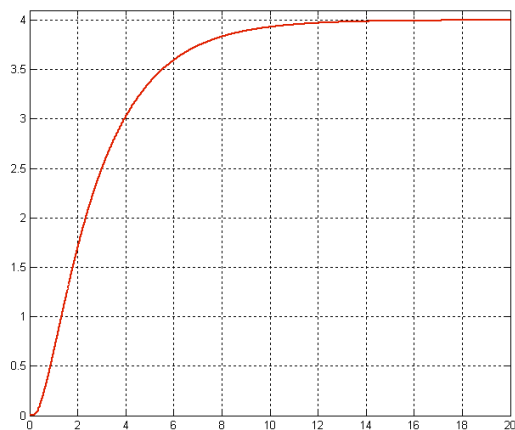
Roll (ψ)



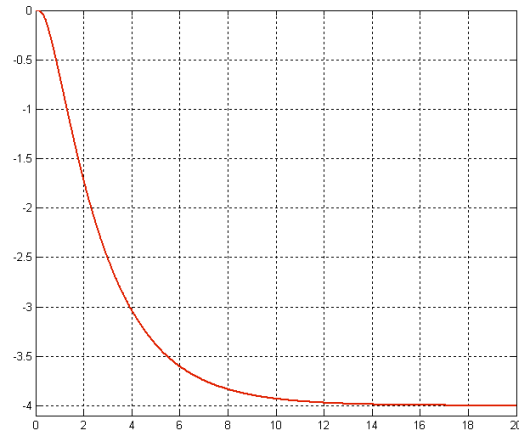
Yaw (Φ)



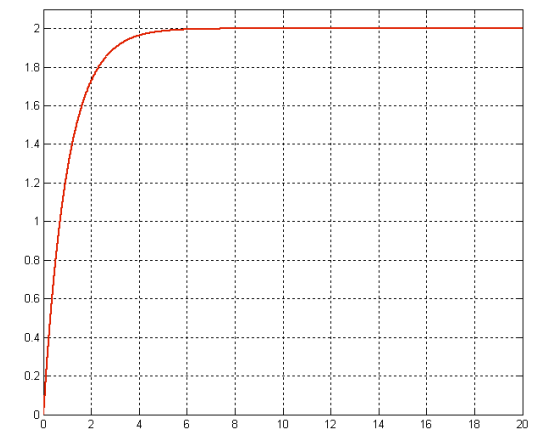
X



Y

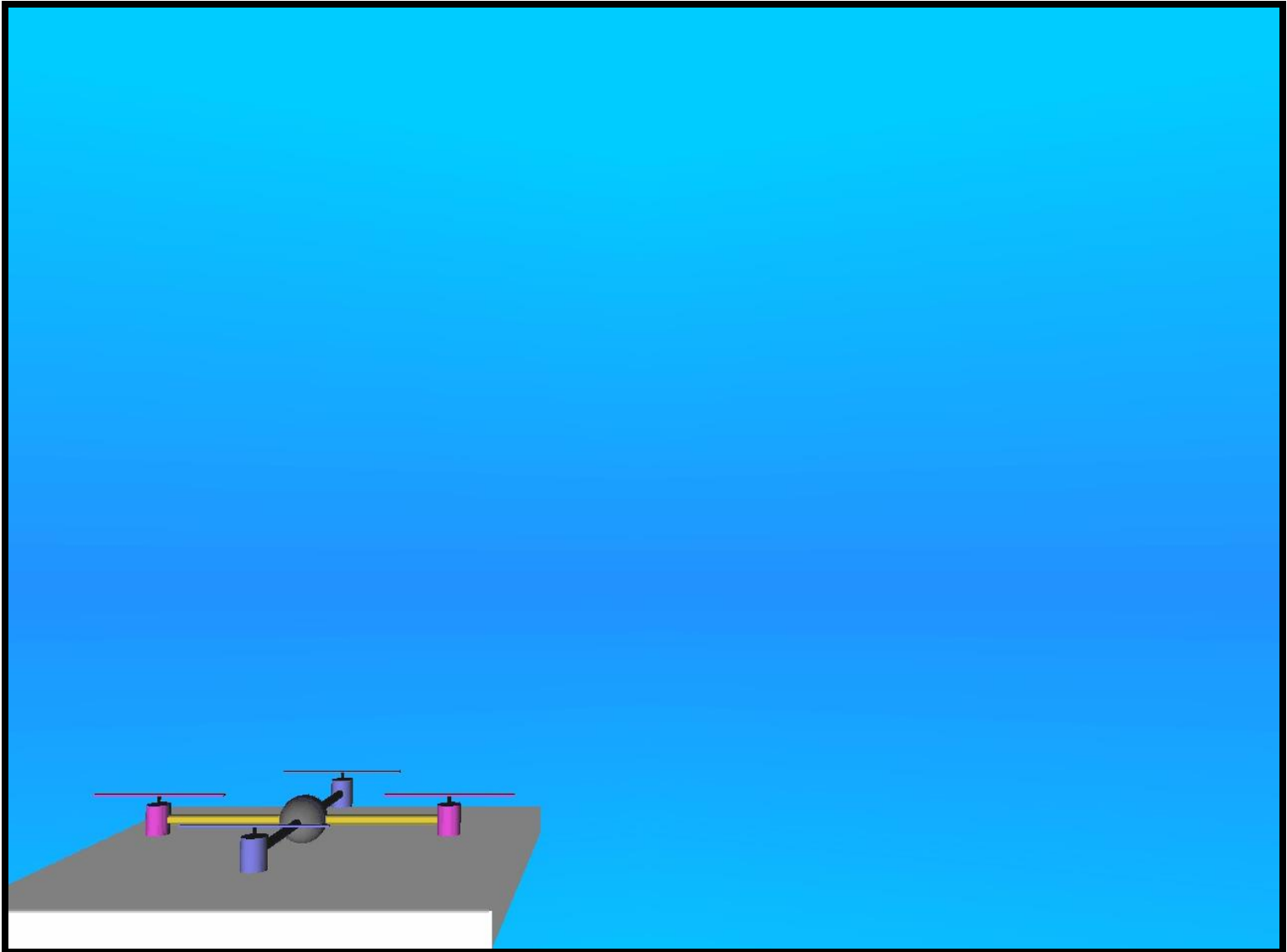
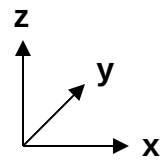


Z



$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

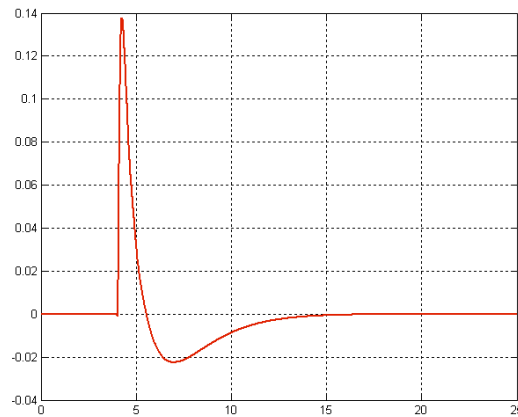
$$Z_d = 1m \quad X_d = 4m \quad \phi_d = \pi/6$$



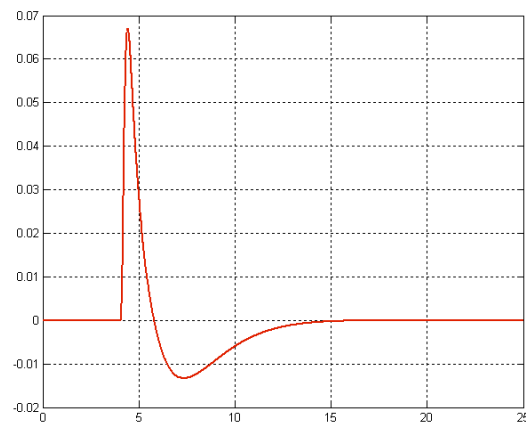
$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 1m \quad X_d = 4m \quad \phi_d = \pi/6$$

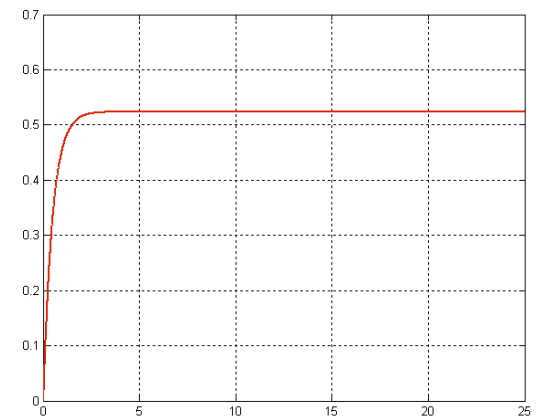
Pitch (θ)



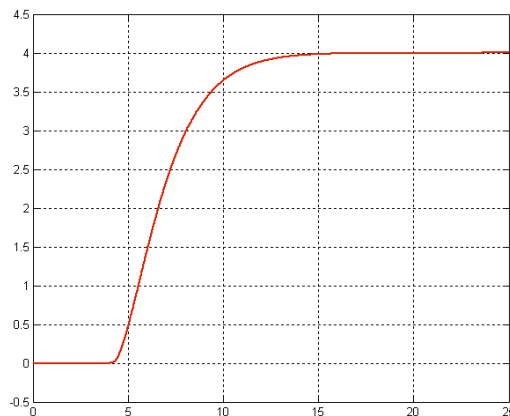
Roll (ψ)



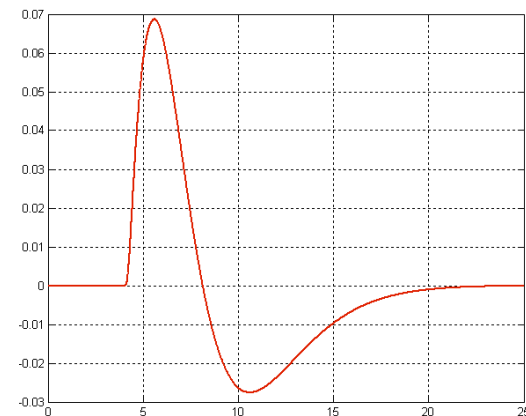
Yaw (Φ)



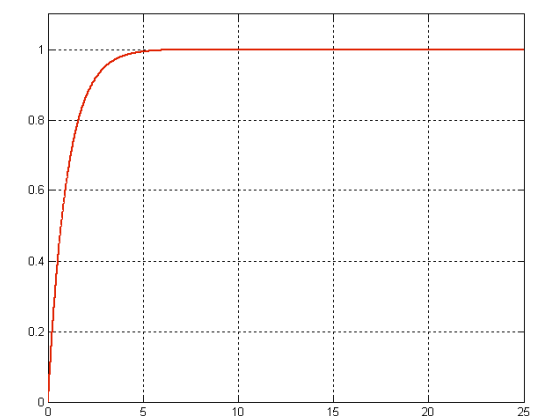
X



Y

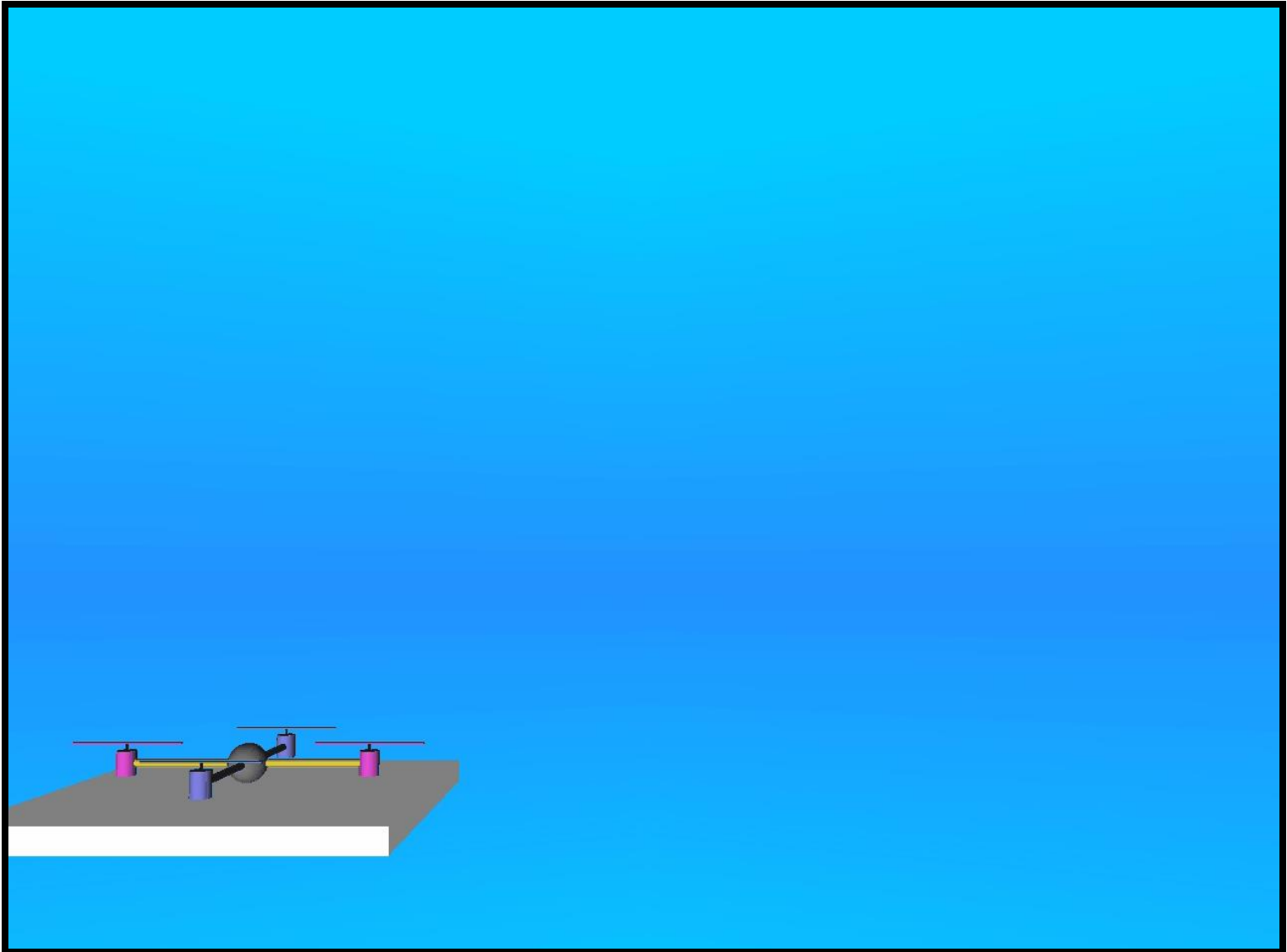
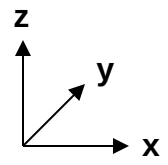


Z



$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

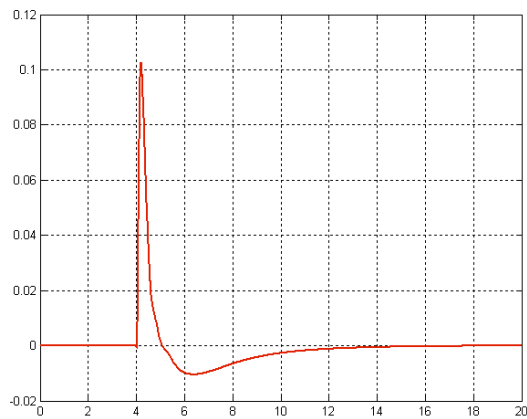
$$Z_d = 1m \quad X_d = 4m \quad Y_d = -4m \quad \phi_d = \pi / 6$$



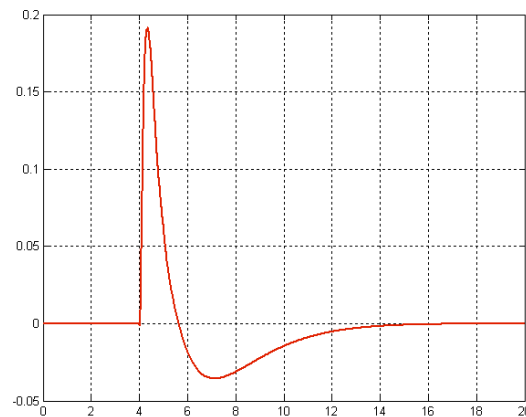
$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

$$Z_d = 1m \quad X_d = 4m \quad Y_d = -4m \quad \phi_d = \pi / 6$$

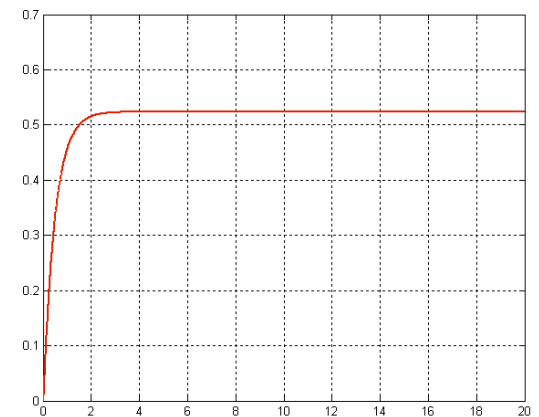
Pitch (θ)



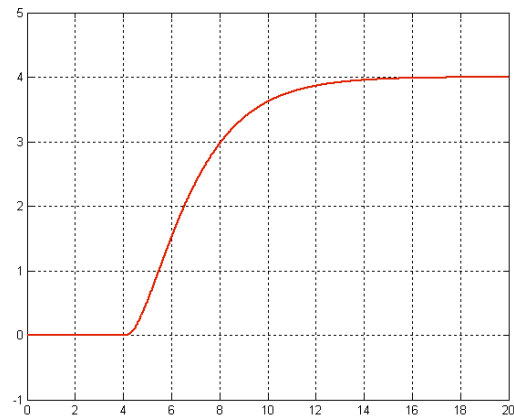
Roll (ψ)



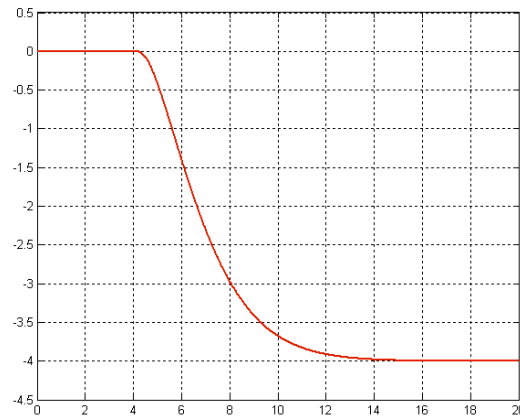
Yaw (Φ)



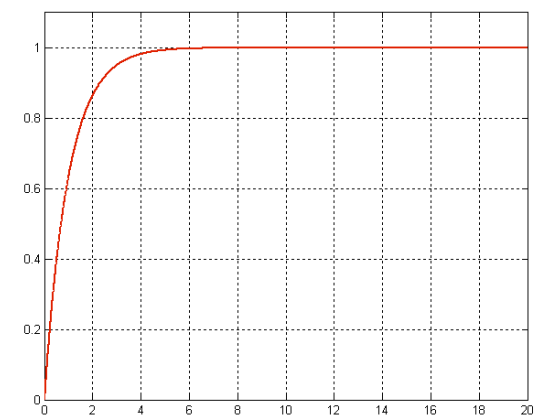
X



Y

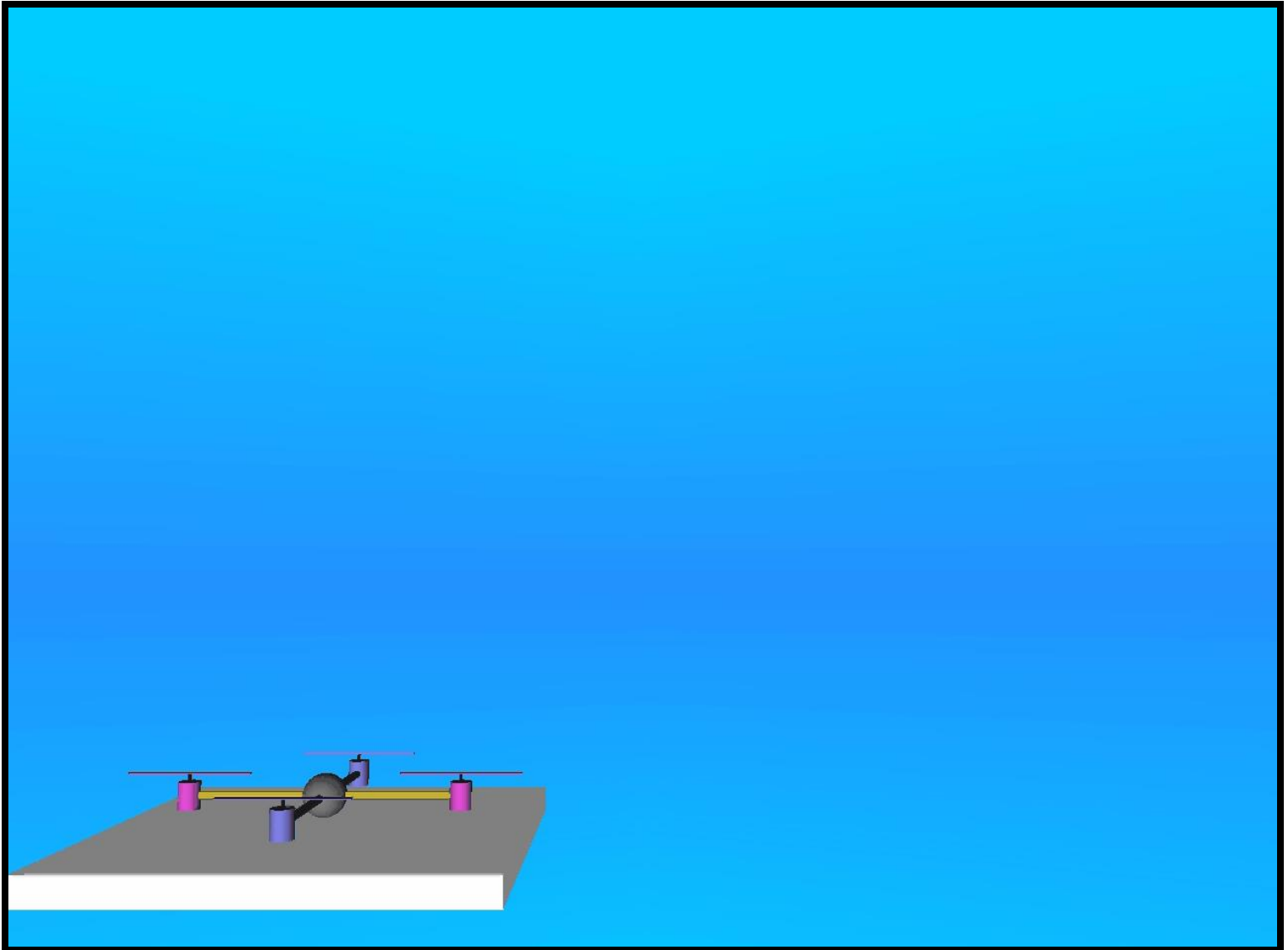
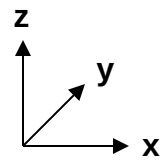


Z



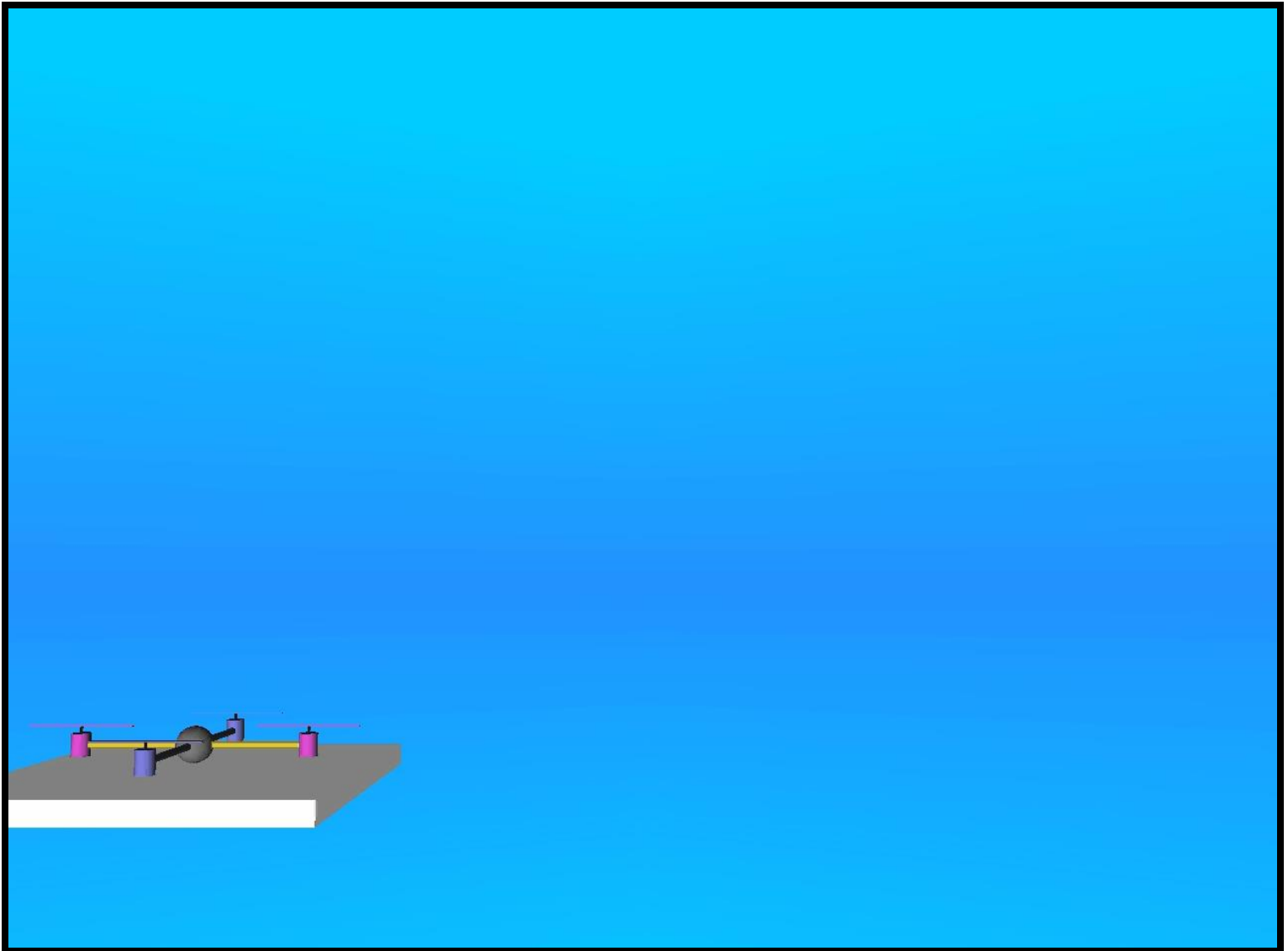
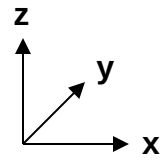
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$$Z_d = 2m \quad X_d = 4m \quad Y_d = -4m \quad \phi_d = \pi / 2$$



$$Z_0 = 0m \quad X_0 = 0m \quad Y_0 = 0m \quad \theta_0 = 0 \quad \psi_0 = 0 \quad \phi_0 = 0$$

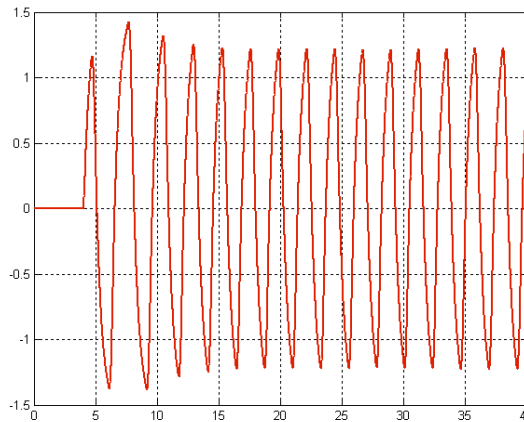
$$Z_d = 2m \quad X_d = 10m \quad Y_d = 10m \quad \phi_d = \pi/3$$



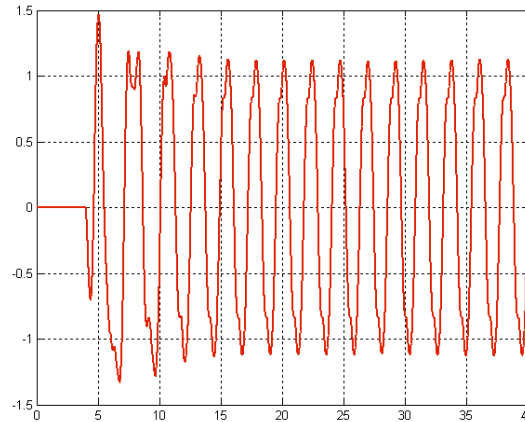
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$$Z_d = 2m \quad X_d = 10m \quad Y_d = 10m \quad \phi_d = \pi/3$$

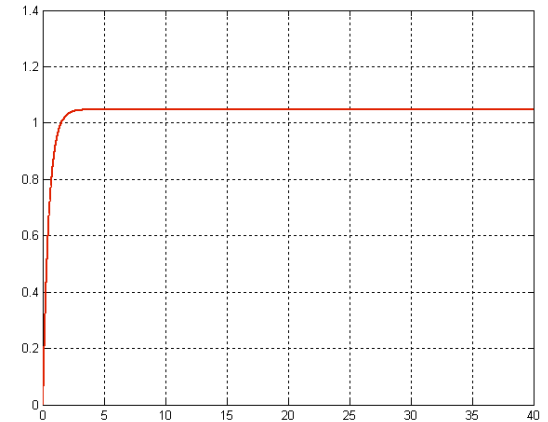
Pitch (θ)



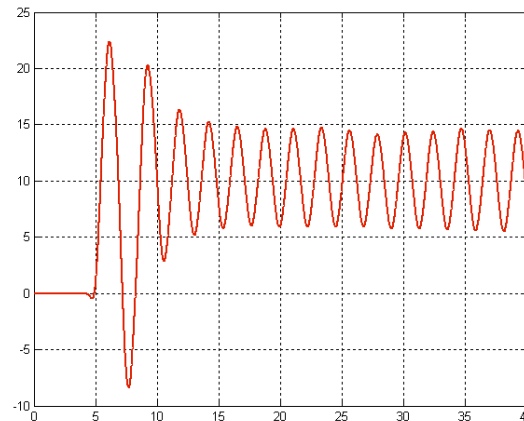
Roll (ψ)



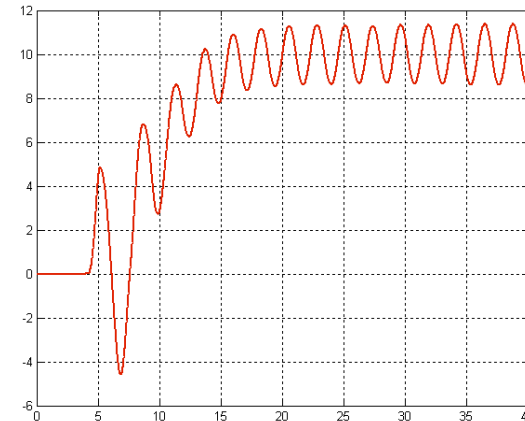
Yaw (Φ)



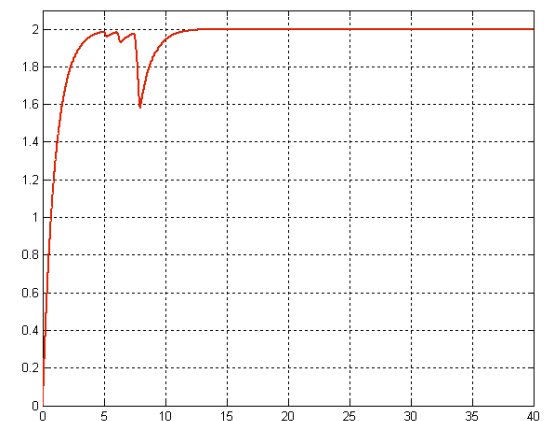
X



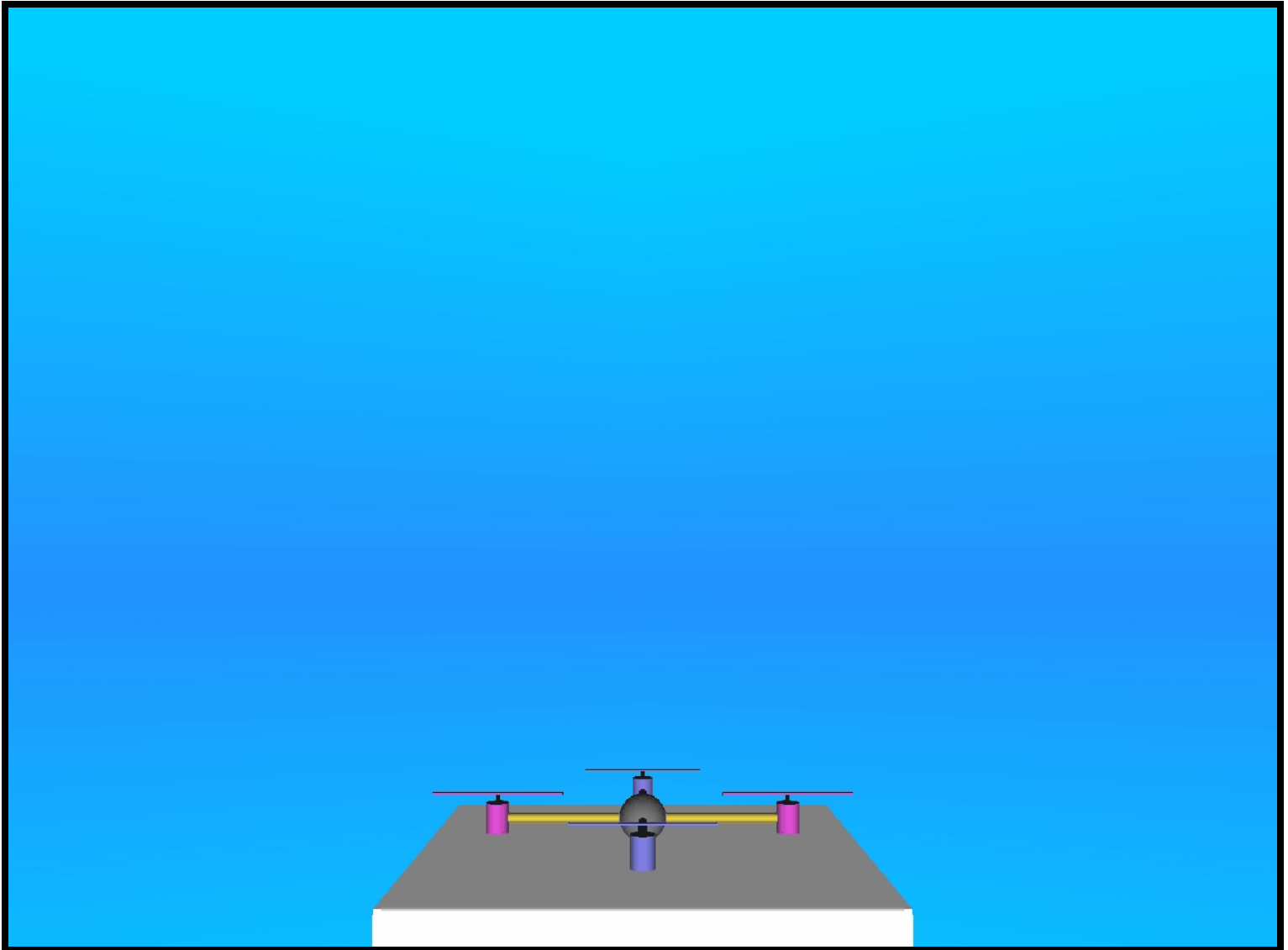
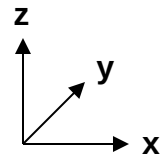
Y



Z



BODY ANGULAR RATES



ATTITUDE & ALTITUDE CONTROL

PLAY WITH ALTITUDE CONTROL

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- [3] S. Bouabdallah, P. Murrieri, R. Siegwart, ***Modeling of the “OS4” Quadrotor v1.0***, Autonomous Systems Laboratory Ecole Polytechnique Federale de Lausanne
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