Active Fault Tolerant Control of Quad-Rotor Helicopter

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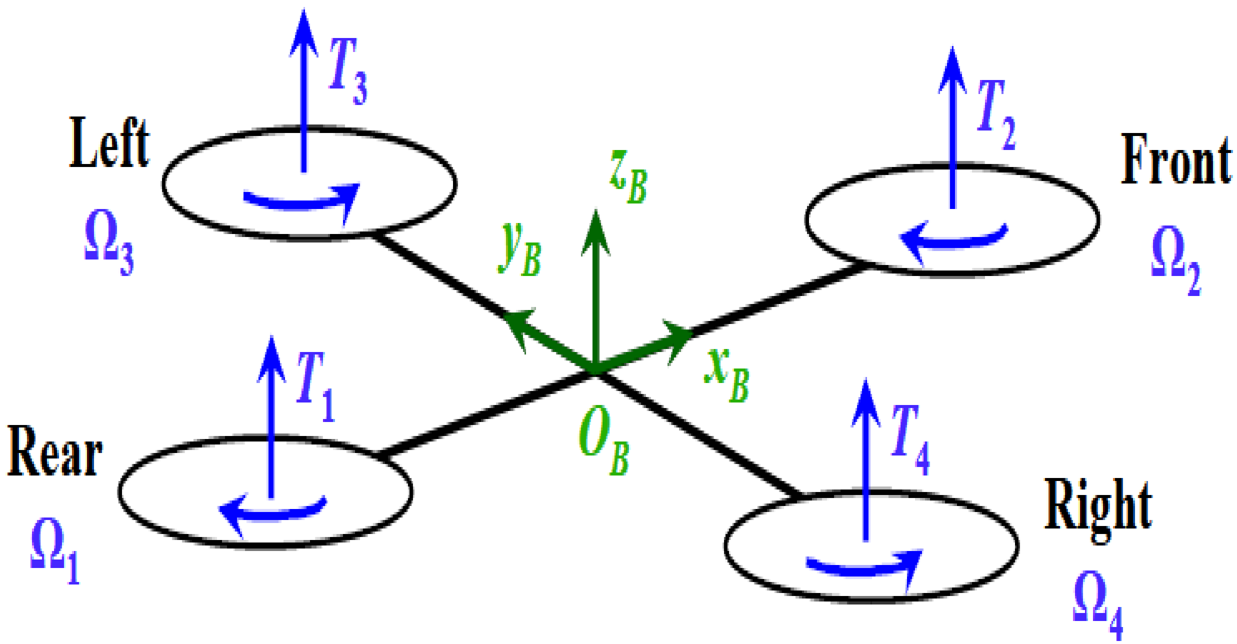
Quad-rotor Model

- 6 degrees of freedom body



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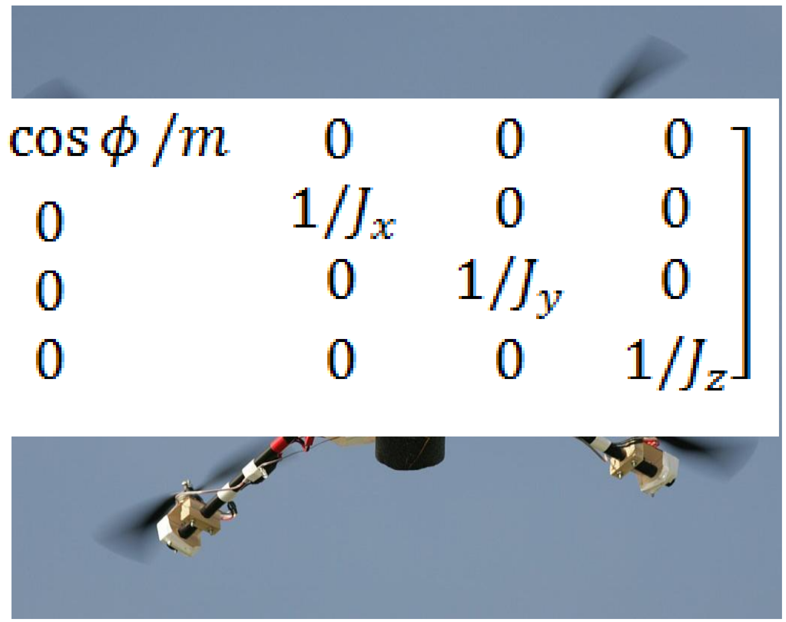
Quad-rotor Model

- Quad-rotor dynamics

$$X = \Psi + \Phi U$$

$$\Psi = \begin{bmatrix} -g \\ -\dfrac{\dot{\theta}\dot{\psi}(J_z - J_y)}{J_x} \\ -\dfrac{\dot{\phi}\dot{\psi}(J_x - J_z)}{J_y} \\ -\dfrac{\dot{\theta}\dot{\phi}(J_y - J_x)}{J_z} \end{bmatrix}$$

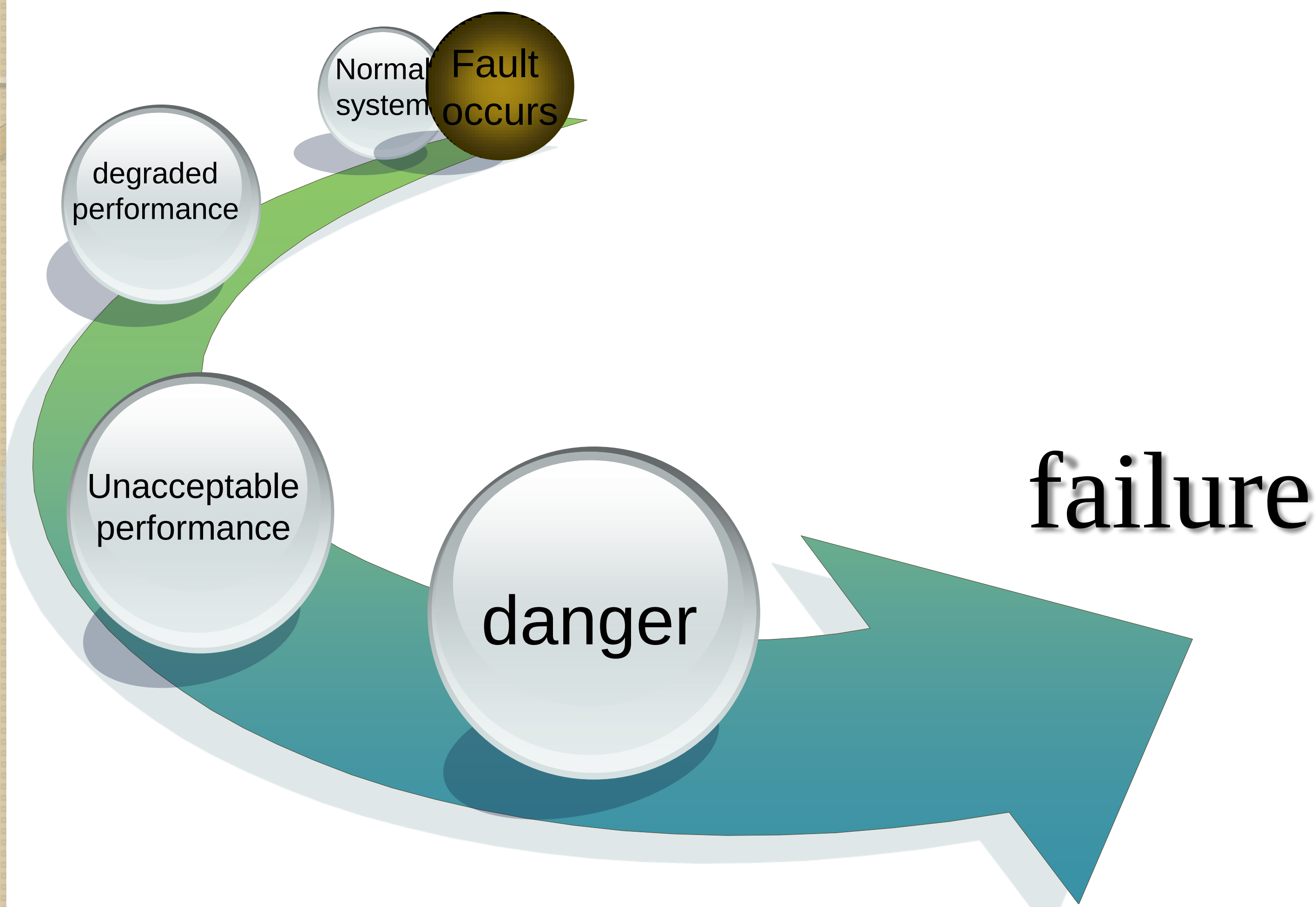
$$X = \begin{bmatrix} z \\ \phi \\ \theta \\ \psi \end{bmatrix} \qquad U = \begin{bmatrix} u_3 \\ u_4 \end{bmatrix}$$



$$\Phi = \begin{bmatrix} \cos\theta\cos\phi/m & 0 & 0 & 0 \\ 0 & 1/J_x & 0 & 0 \\ 0 & 0 & 1/J_y & 0 \\ 0 & 0 & 0 & 1/J_z \end{bmatrix}$$

X. Zhang, Y. Zhang, “Fault Tolerant Control for Quad-rotor UAV by Employing Lyapunov- based Adaptive Control Approach”, AIAA Guidance, Navigation, and Control Conference, Toronto, Canada, Aug. 2010.

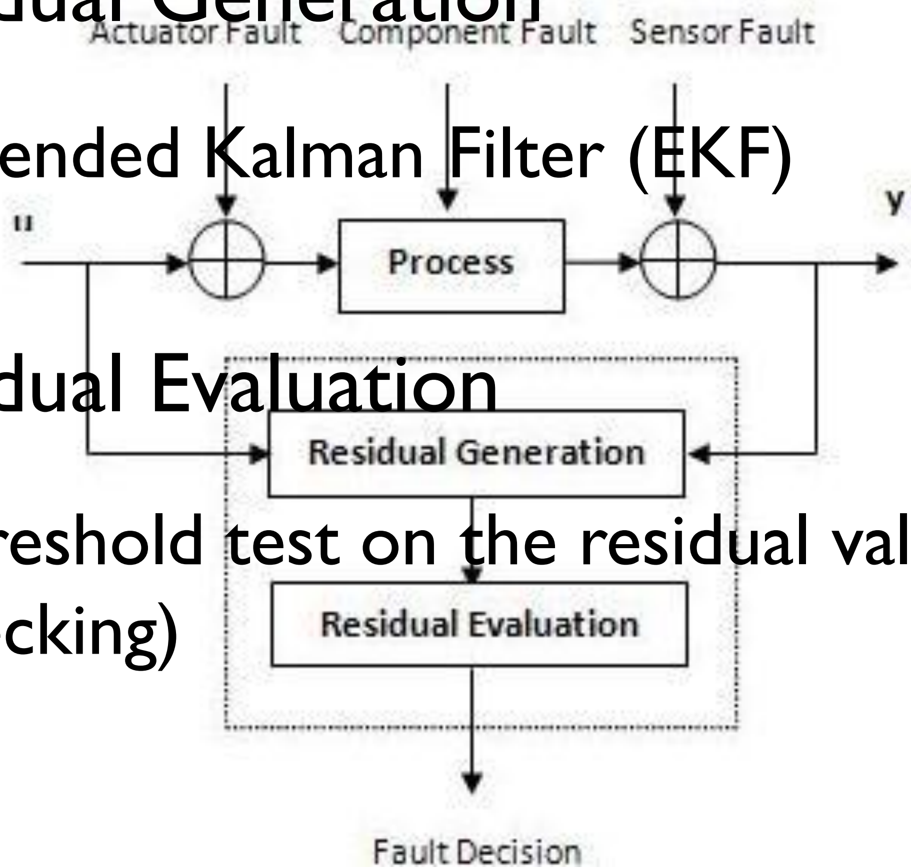
Fault Detection



M. Witczak, Modelling and Estimation Strategies for Fault Diagnosis of Non-Linear Systems, Berlin : Springer, 2007.

Fault Detection

- Residual Generation
  - Extended Kalman Filter (EKF)
- Residual Evaluation
  - Threshold test on the residual value (limit checking)



Fault Detection: Residual Generation

- System equation in state space form
- Extended Kalman Filter

$$\dot{X} = f(X, u)$$

$$X = \begin{bmatrix} z \\ \phi \\ \theta \\ \psi \\ \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$

$$f(X, u) = \begin{bmatrix} \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \\ -g + \dfrac{b_1 \cos\theta \cos\phi \, u_1}{m} \\ \dfrac{\dot{\theta}\dot{\psi}(J_z - J_y) + b_2 l u_2}{J_x} \\ \dfrac{\dot{\phi}\dot{\psi}(J_x - J_z) + b_3 l u_3}{J_y} \\ \dfrac{\dot{\theta}\dot{\phi}(J_y - J_x) + b_4 l u_4}{J_z} \end{bmatrix}$$

$$\Phi(k) \triangleq \frac{\partial f(X(k), u(k), k)}{\partial X(k)} \Big| X(k) = \hat{X}(k|k)$$

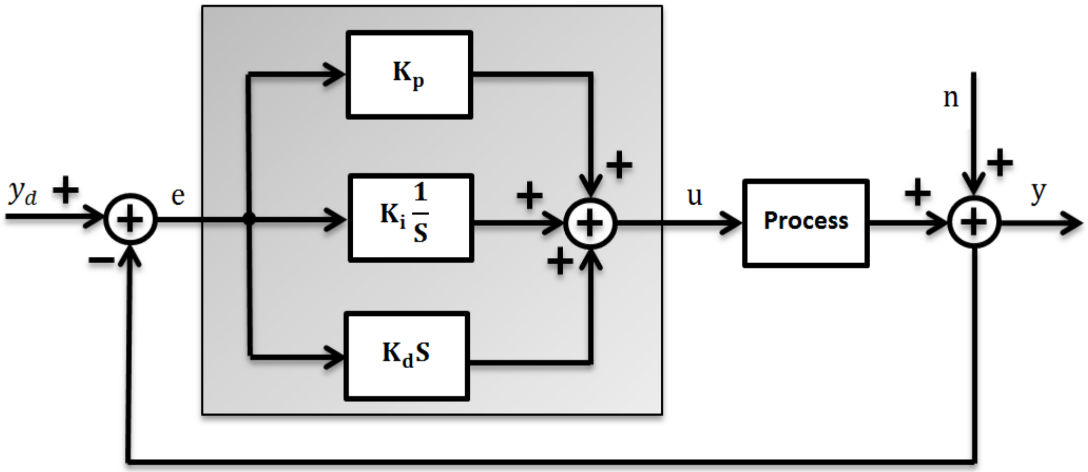
$$H(k+1) \triangleq \frac{\partial h(X(k+1), k)}{\partial X(k+1)} \Big| X(k+1) = \hat{X}(k+1|k)$$

Fault detection: Residual Evaluation

- Time window → 10 iterations

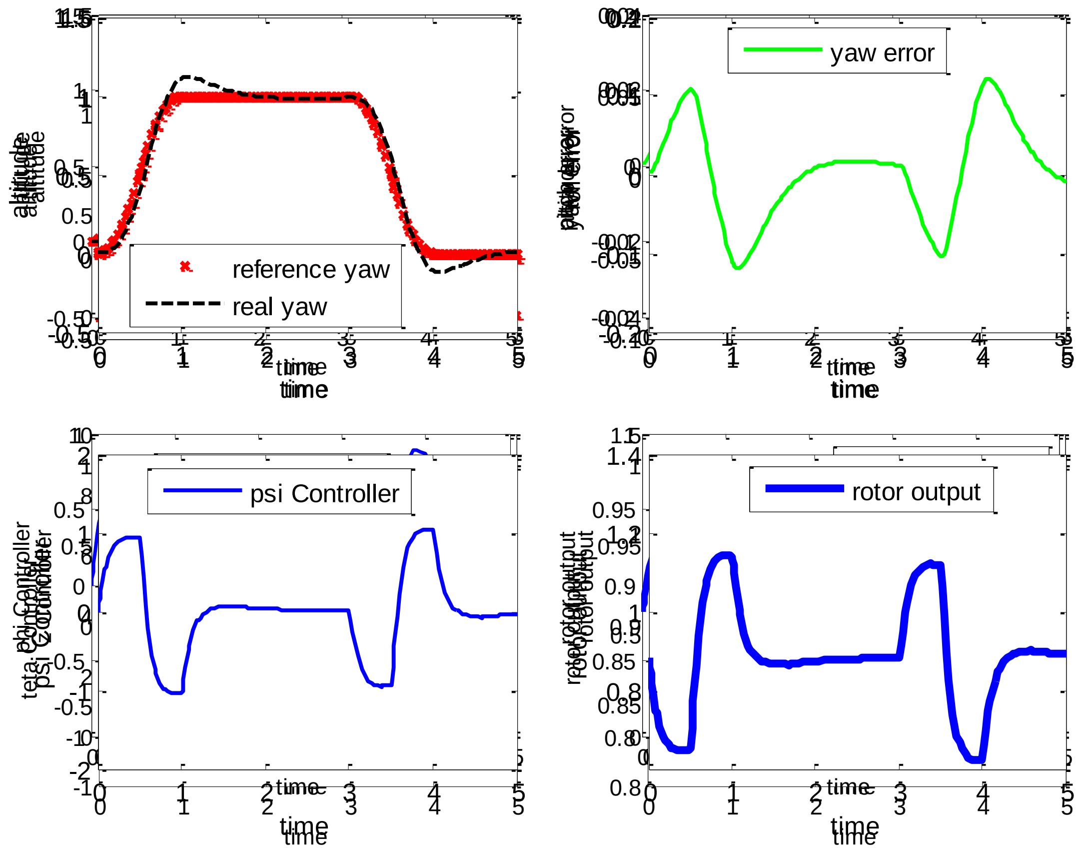
- Threshold
$$\begin{cases} |r| > -0.3 & fault \\ |r| < 0.3 & fault\ free \end{cases}$$

PID Controller



K_p	K_i	K_d
30	20	24

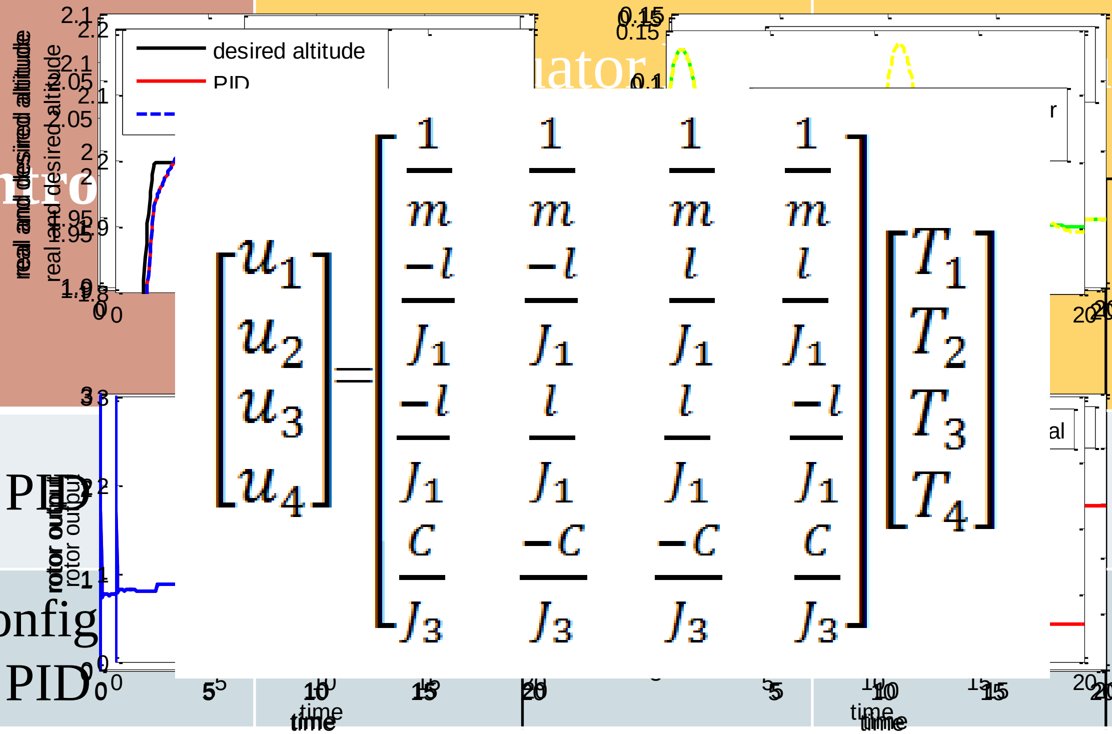
PID Controller



PID controller for quad-rotor helicopter

PID and Reconfigured PID

Contro	ator	ator loss	
			Reconfigured Time
PID			8.2
Reconfig PID			7.2

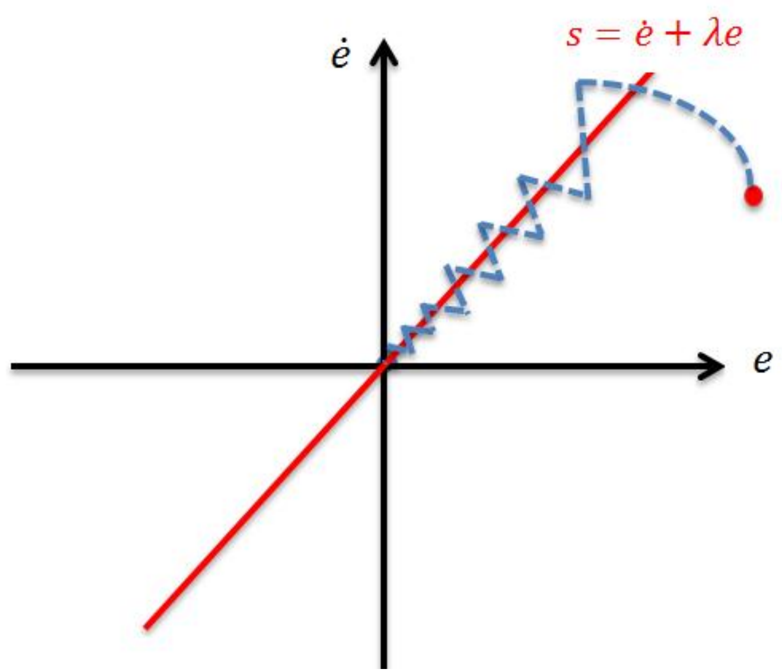


$$\begin{bmatrix}u_1\\u_2\\u_3\\u_4\end{bmatrix}=\begin{bmatrix}\frac{1}{m} & \frac{1}{m} & \frac{1}{m} & \frac{1}{m}\\ \frac{-l}{J_1} & \frac{-l}{J_1} & \frac{l}{J_1} & \frac{l}{J_1}\\ \frac{-l}{J_1} & \frac{l}{J_1} & \frac{l}{J_1} & \frac{-l}{J_1}\\ \frac{c}{J_3} & \frac{-c}{J_3} & \frac{-c}{J_3} & \frac{c}{J_3}\end{bmatrix}\begin{bmatrix}T_1\\T_2\\T_3\\T_4\end{bmatrix}$$

50% loss of all rotors

30% loss of T1

Sliding Mode Controller



$\ddot{X} = f(X)$

$g_s = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

$v = g_s u_s$

$\ddot{X} = f(X)$

G :

$$\ddot{z} = Bu - g, e = z - z^d$$

U =

$$s = \dot{e} + ke$$

$ign(S^T)]$

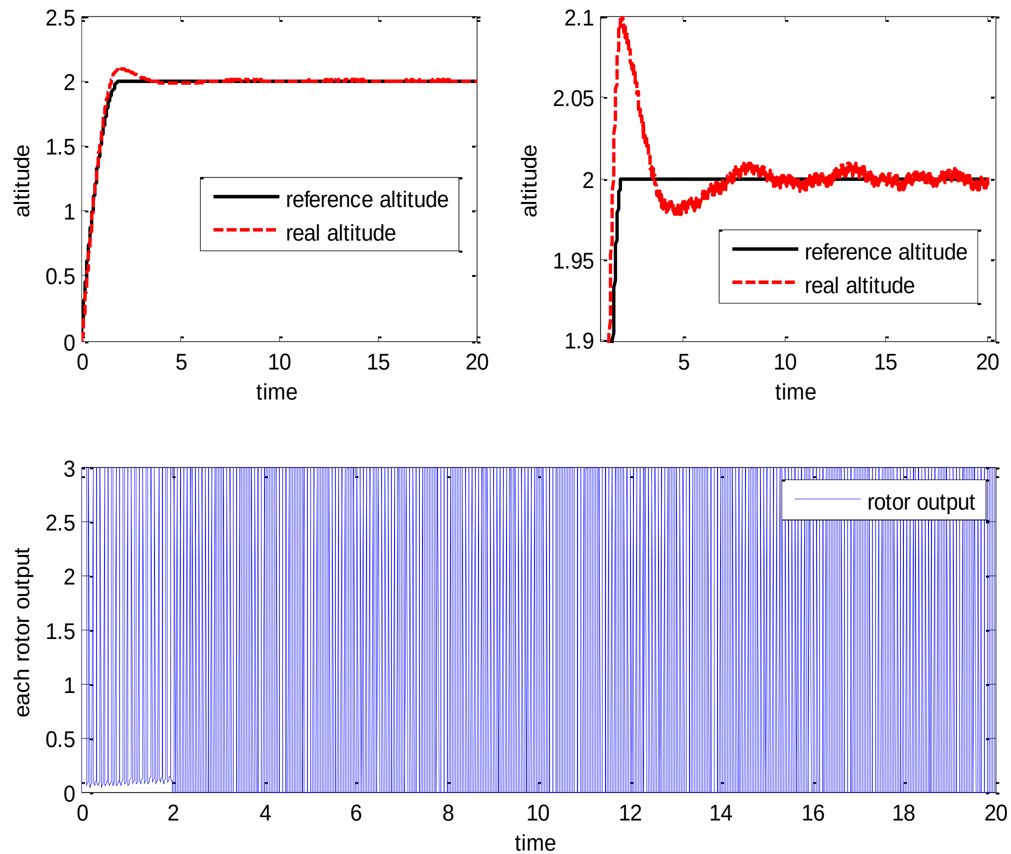
$$\dot{s} = \ddot{e} + k\dot{e} = \ddot{z} - \ddot{z}^d + k\dot{e} = Bu - g - \ddot{z}^d + k\dot{e} = 0$$

$$\rightarrow u = B^{-1}(g + \ddot{z}^d - k\dot{e})$$

D. Lee, H. J. K ... de Control for a
Quadrotor Heli ... 2009, PP. 419-428

Sliding Mode Controller

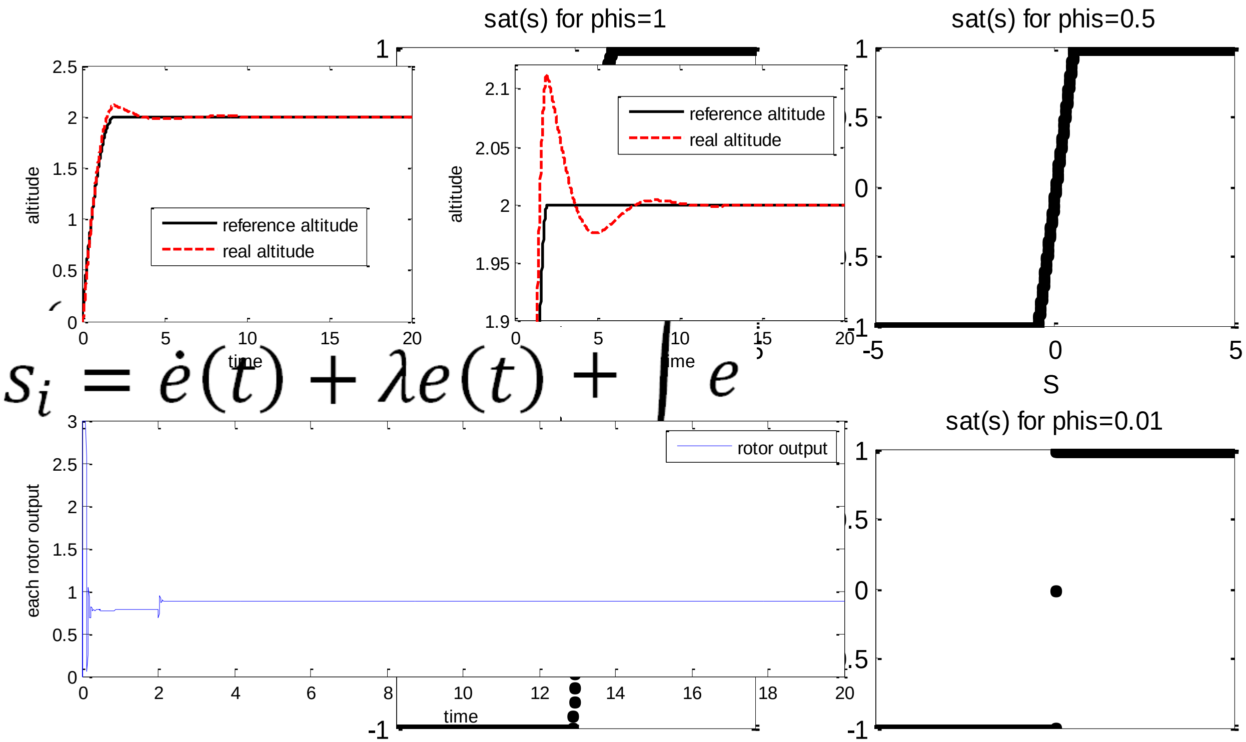
K_1	K_2	K_3	K_4	K_5	K_6
1	1	7	5	5	10



sliding mode control of quad-rotor using sign function

Sliding Mode Control

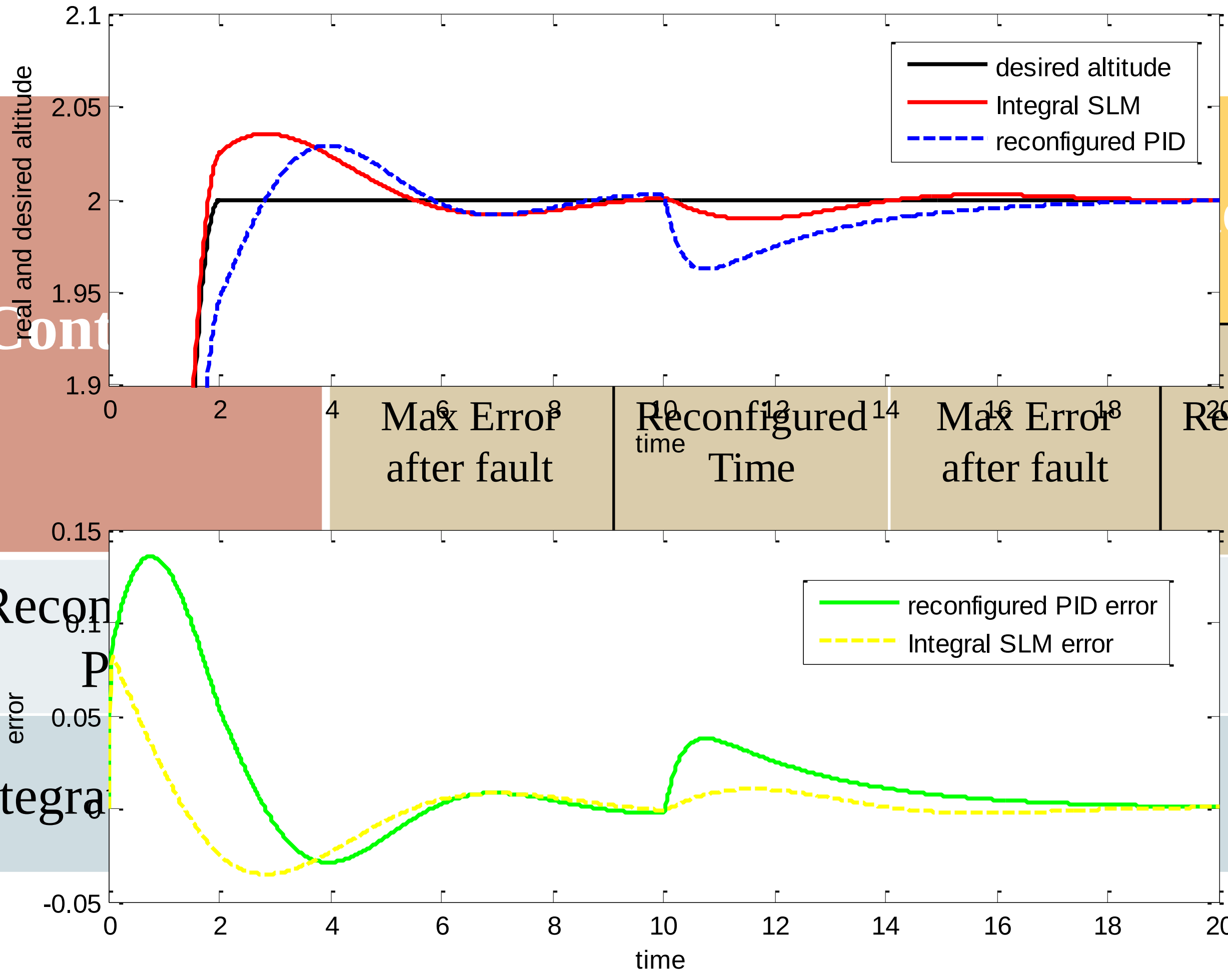
$$sat(s) = \begin{cases} si \\ \dfrac{s}{\varphi_s} \end{cases} \quad s_i = \dot{e}(t) + \lambda e(t) + \int e$$



sliding mode control of quad-rotor using saturation function

Ali Chamseddine, H. Noura, Control and Sensor Fault Tolerance of Vehicle Active Suspension. IEEE Transactions on Control Systems Technology, Vol. 16, NO. 3, May 2008, pp. 416-433.
Ali J. Koshkouei and Keith J. Burnham. Control of DC Motors Using Proportional Integral Sliding Mode. Control Theory and Applications Centre, Coventry University, Coventry CV1 5FB, UK.

Comparison



Reconfigured PID and integral sliding mode controller under 50 % actuator fault

Cont				or loss
	Max Error after fault	Reconfigured Time	Max Error after fault	Reconfigured Time
Recon P				7.2
Integra				6.5

Conclusion

- Quad-rotor modeled
- PID and Sliding mode controller implemented
- PID controller performance in fault tolerant improved by Extended Kalman filter and gain scheduling
- Sliding mode performance improved by adding integral to sliding surface
- Integral sliding mode seems the best between other methods

Thank You !