Active Fault Tolerant Control for Quad-Rotor UAV

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Outline

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- **Active Fault Tolerant Control Strategy**
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- **Linear System Modeling**
- **Active Fault Tolerant Control Strategy**
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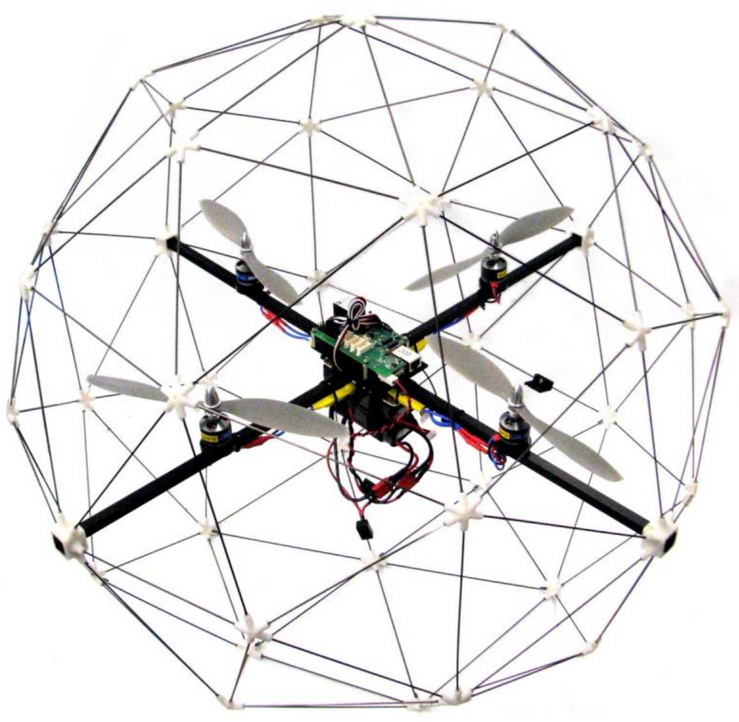
  - **Fault Detection and Diagnosis Integrated with Reconfiguration Mechanism**
  - **Simulation Results**
- **Conclusion**

Quad – Rotor System Modeling



Navigation Equations:

$$\ddot{x} = \frac{F_1 + F_2 + F_3 + F_4}{m}(\cos\psi \sin\theta \cos\phi + \sin\psi \sin\phi) - \frac{k_{d1}\dot{x}}{m}$$

$$\ddot{y} = \frac{F_1 + F_2 + F_3 + F_4}{m}(\sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi) - \frac{k_{d2}\dot{y}}{m}$$

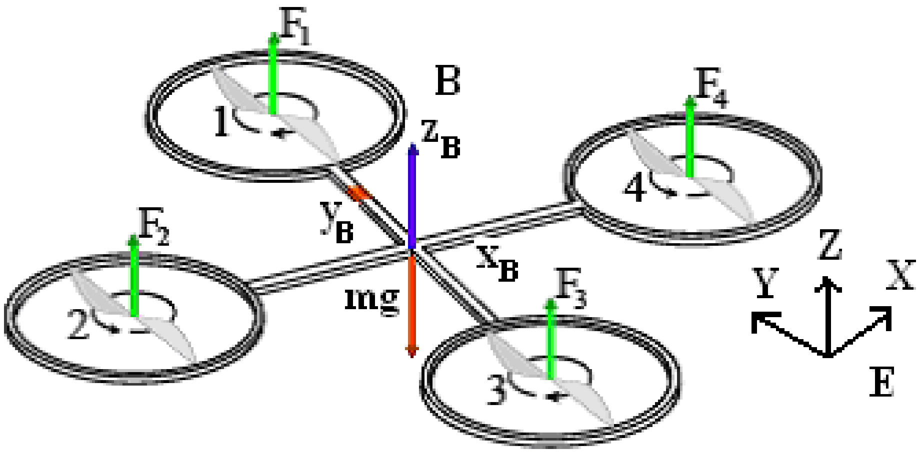
$$\ddot{z} = \frac{F_1 + F_2 + F_3 + F_4}{m}\cos\theta \cos\phi - \frac{k_{d3}\dot{z}}{m} - g$$

Moment Equations:

$$\ddot{\phi} = \frac{1}{J_x}[(F_2 - F_4)l - k_{d4}\dot{\phi} - \dot{\theta}\dot{\psi}(J_z - J_y)]$$

$$\ddot{\theta} = \frac{1}{J_y}[(F_1 - F_3)l - k_{d5}\dot{\theta} - \dot{\phi}\dot{\psi}(J_x - J_z)]$$

$$\ddot{\psi} = \frac{1}{J_z}[(F_1 - F_2 + F_3 - F_4)l - k_{d6}\dot{\psi} - \dot{\theta}\dot{\phi}(J_y - J_x)]$$

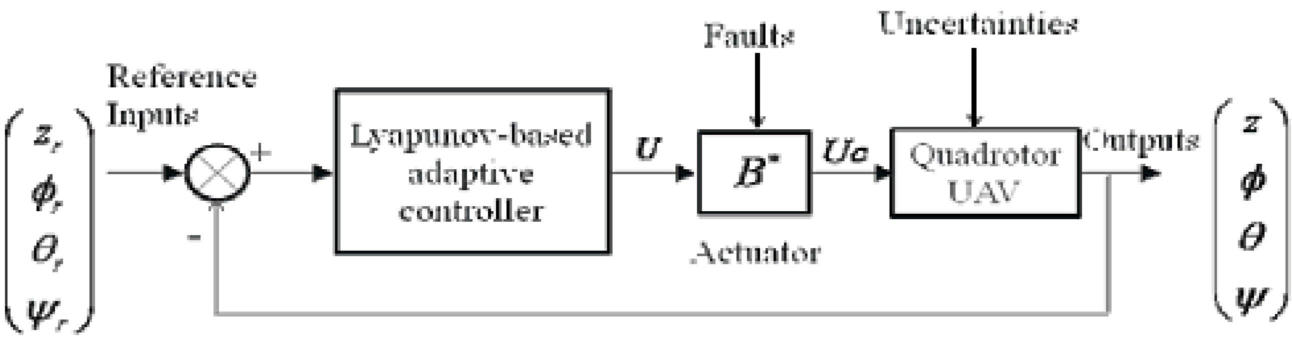


$$F_i = b_i \omega_i^2$$

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{pmatrix} = \begin{pmatrix} F_1 + F_2 + F_3 + F_4 \\ F_2 - F_4 \\ F_1 - F_3 \\ F_1 + F_3 - F_2 - F_4 \end{pmatrix} = \begin{pmatrix} b_1 & b_2 & b_3 & b_4 \\ 0 & b_2 & 0 & -b_4 \\ b_1 & 0 & -b_3 & 0 \\ b_1 & -b_2 & b_3 & -b_4 \end{pmatrix} \begin{pmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{pmatrix}$$

Active Fault Tolerant Control Strategy

- **Adaptive Lyapunov-based Method**



$$\begin{pmatrix}\ddot{z}\\ \ddot{\phi}\\ \ddot{\theta}\\ \ddot{\psi}\end{pmatrix} = \begin{pmatrix} -g \\ \frac{-\dot{\theta}\dot{\psi}(J_z-J_y)}{J_x} \\ \frac{-\dot{\phi}\dot{\psi}(J_x-J_z)}{J_y} \\ \frac{-\dot{\theta}\dot{\phi}(J_y-J_x)}{J_z}\end{pmatrix} + \begin{pmatrix} b_1^*\frac{\cos\theta\cos\phi}{m} & 0 & 0 & 0\\ 0 & b_2^*\frac{l}{J_x} & 0 & 0\\ 0 & 0 & b_3^*\frac{l}{J_y} & 0\\ 0 & 0 & 0 & b_4^*\frac{l}{J_z}\end{pmatrix}\begin{pmatrix}u_1\\ u_2\\ u_3\\ u_4\end{pmatrix}$$

$$B^* = \begin{pmatrix} b_1^* & 0 & 0 & 0\\ 0 & b_2^* & 0 & 0\\ 0 & 0 & b_3^* & 0\\ 0 & 0 & 0 & b_4^*\end{pmatrix}$$

Lyapunov Adaptive Control Algorithm Equations

Quad – Rotor Altitude Equations

$$\ddot{z} = b_1^* \frac{u_1}{m} \cos\theta \cos\phi - g$$

$$u_1 = \hat{\alpha}_1 u_{c1}$$

$$u_{c1} = \frac{m}{\cos\theta \cos\varphi}(-c_{12} y_{12} - y_{11} + g + \ddot{z}_r + \dot{\beta}_1)$$

$$\dot{\hat{\alpha}}_1 = -\gamma \frac{u_{c1}}{m} \cos\theta \cos\varphi \, y_{12}$$

$$y_{11}(t) = z(t) - z_r(t)$$

$$y_{12}(t) = \dot{z}(t) - \dot{z}_r(t) - \beta_1$$

$$\beta_1(t) = -c_{11} y_{11}(t)$$

$$\alpha_1 \stackrel{\Delta}{=} \frac{1}{b_1^*}$$

Cont.

Quad – Rotor Angles Equations

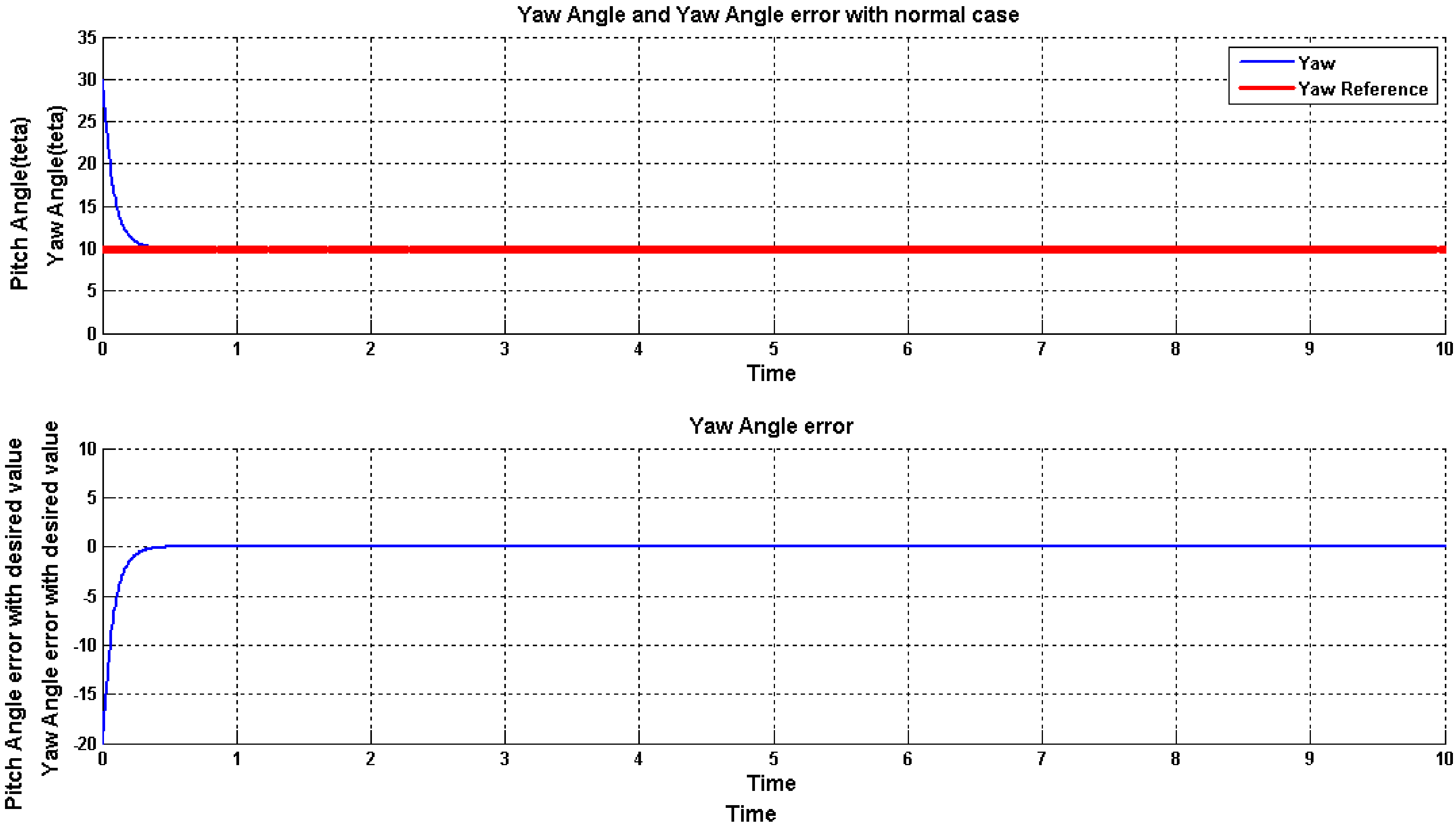
$$u_{c2} = \frac{J_x}{l}[-c_{22}y_{22} - y_{21} + \dot{\beta}_2 + \ddot{\phi}_r + \frac{1}{J_x}\dot{\theta}\dot{\psi}(J_z - J_y)] \qquad u_2 = \hat{\alpha}_2 u_{c2}$$

$$u_{c3} = \frac{J_x}{l}[-c_{32}y_{32} - y_{31} + \dot{\beta}_3 + \ddot{\theta}_r + \frac{1}{J_y}\dot{\phi}\dot{\psi}(J_x - J_z)] \qquad u_3 = \hat{\alpha}_3 u_{c3}$$

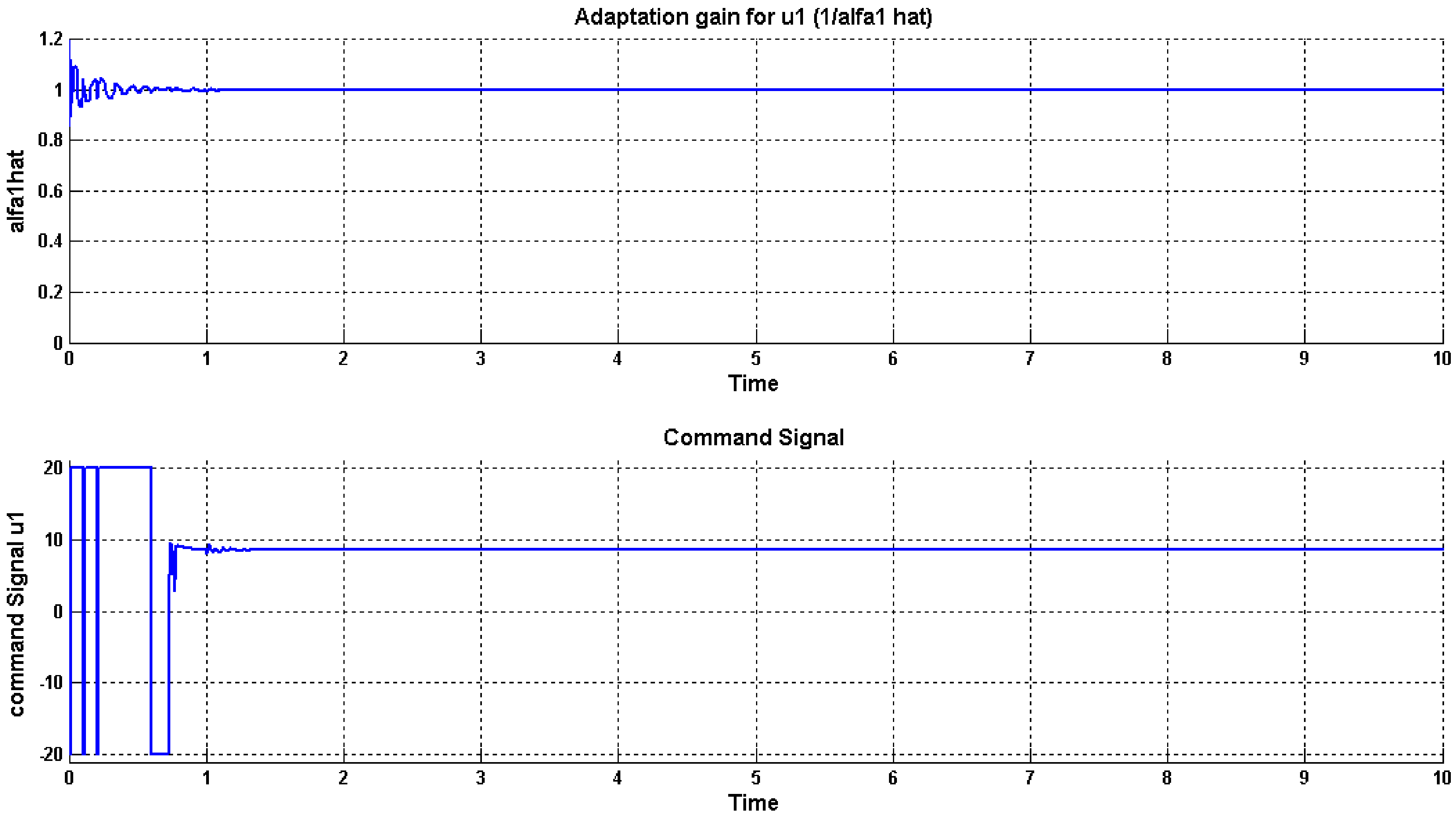
$$u_{c4} = \frac{J_x}{l}[-c_{42}y_{22} - y_{41} + \dot{\beta}_4 + \ddot{\psi}_r + \frac{1}{J_z}\dot{\theta}\dot{\phi}(J_y - J_x)] \qquad u_4 = \hat{\alpha}_4 u_{c4}$$

Simulation Results for Lyapunov-Based Adaptive Control

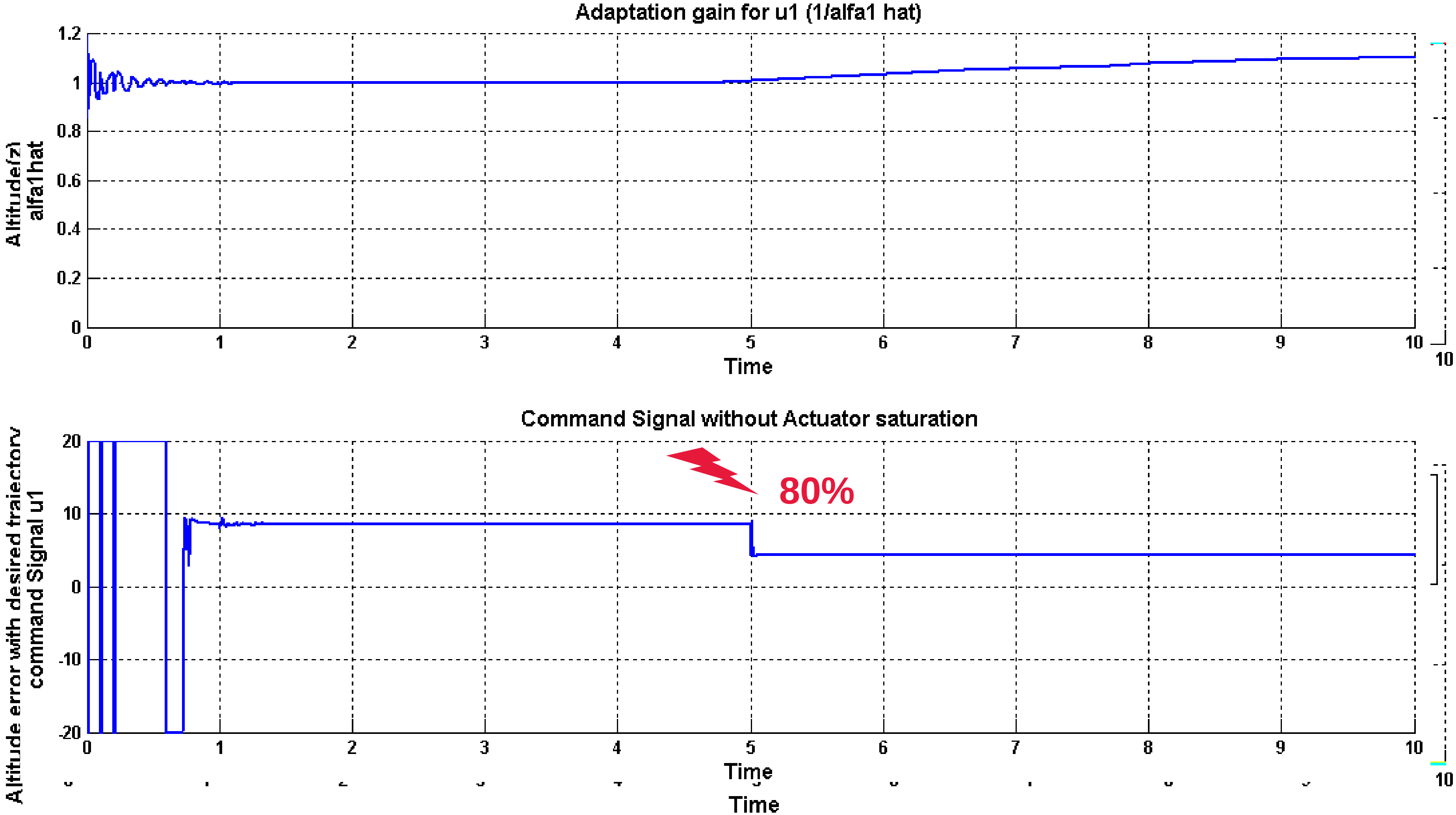
- Normal Case (Without Fault)



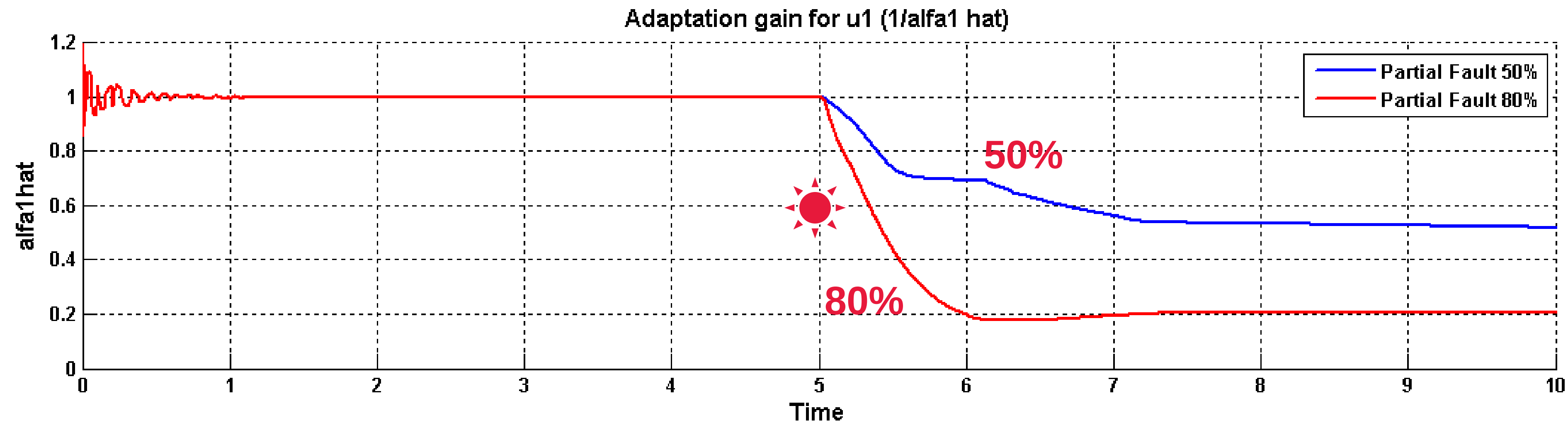
- Normal Case (With Saturation on Altitude Actuator)

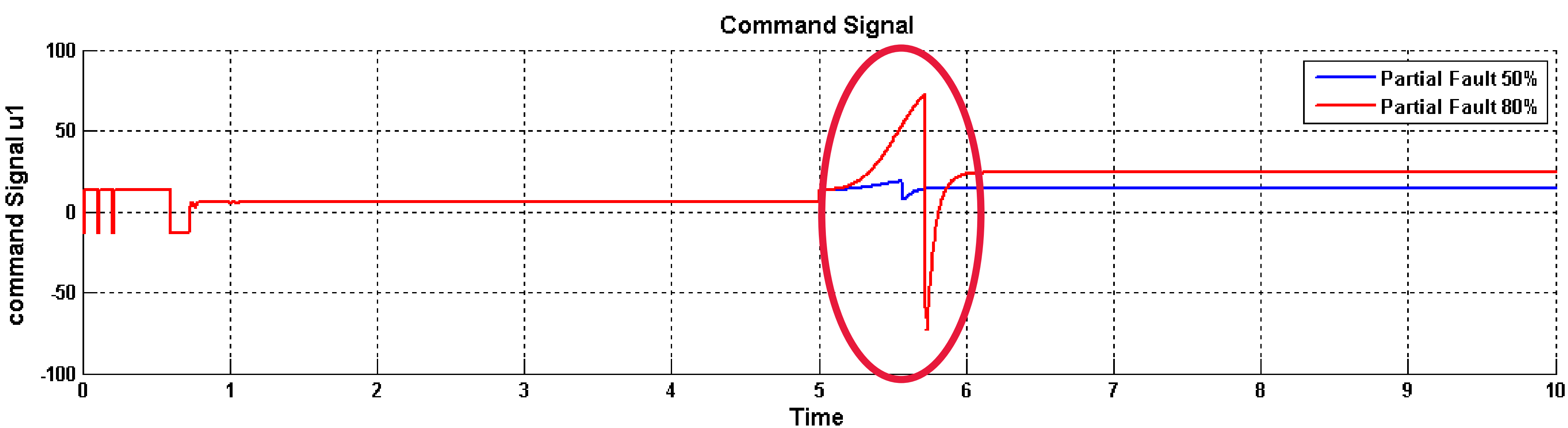


- With Uncertainty in System Parameters at t = 5 sec

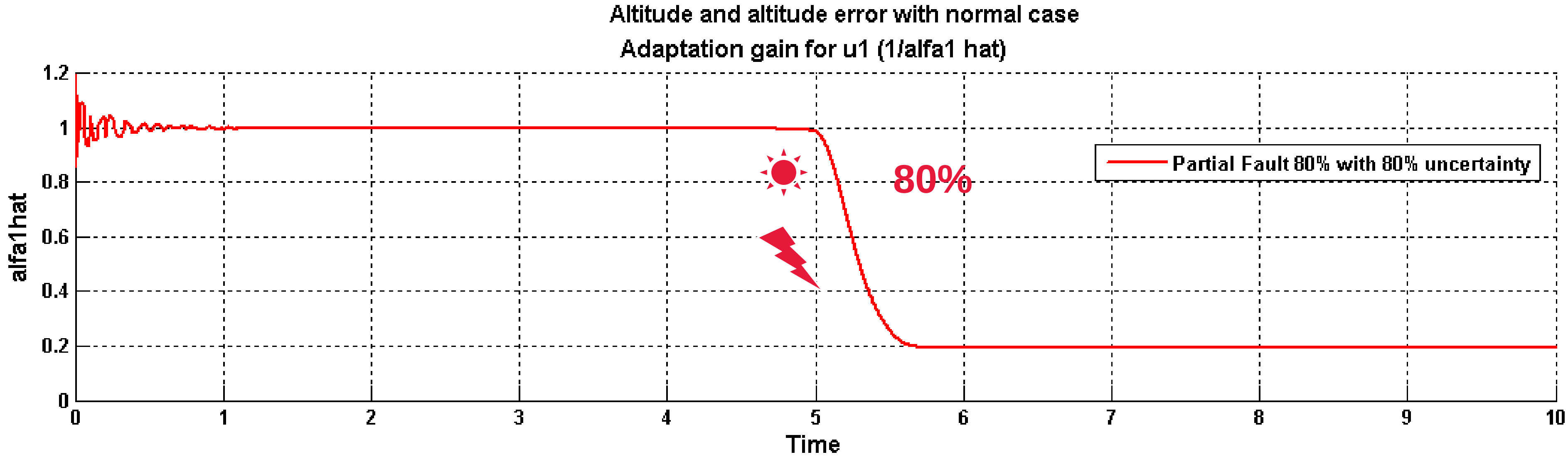


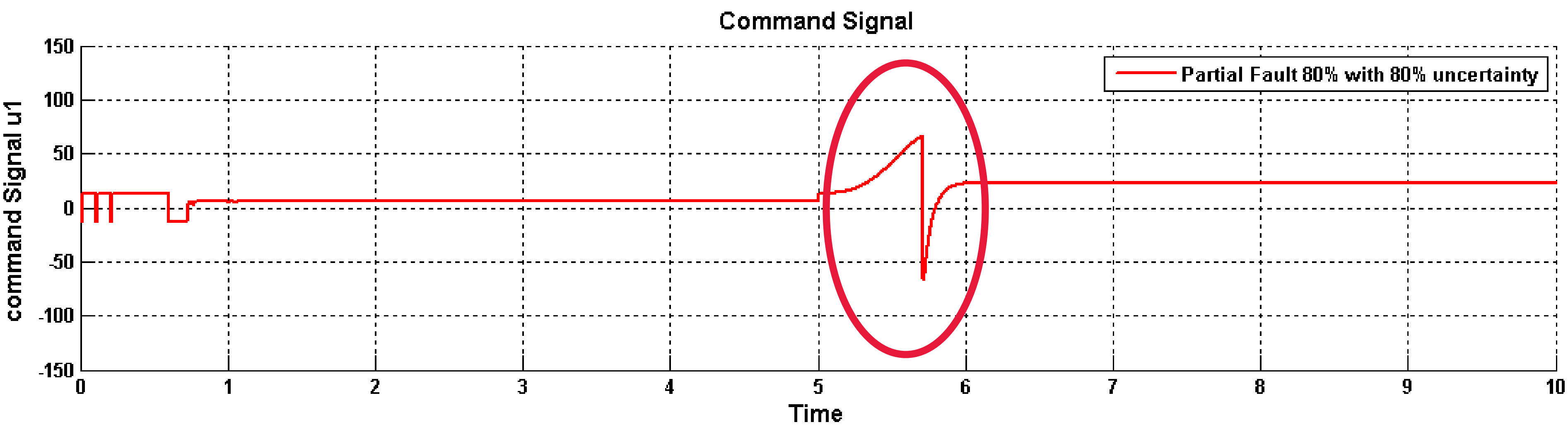
- Partial Fault in Altitude Control Actuator at t = 5 sec





- Partial Fault and Uncertainty at t = 5 sec





Adaptive λ – Tracking Method

- Introduction to λ – Tracking Method

The output is controlled to a λ neighborhood of the set point.

$$\left| y(t) - y_{ref}(t) \right| \le \lambda$$

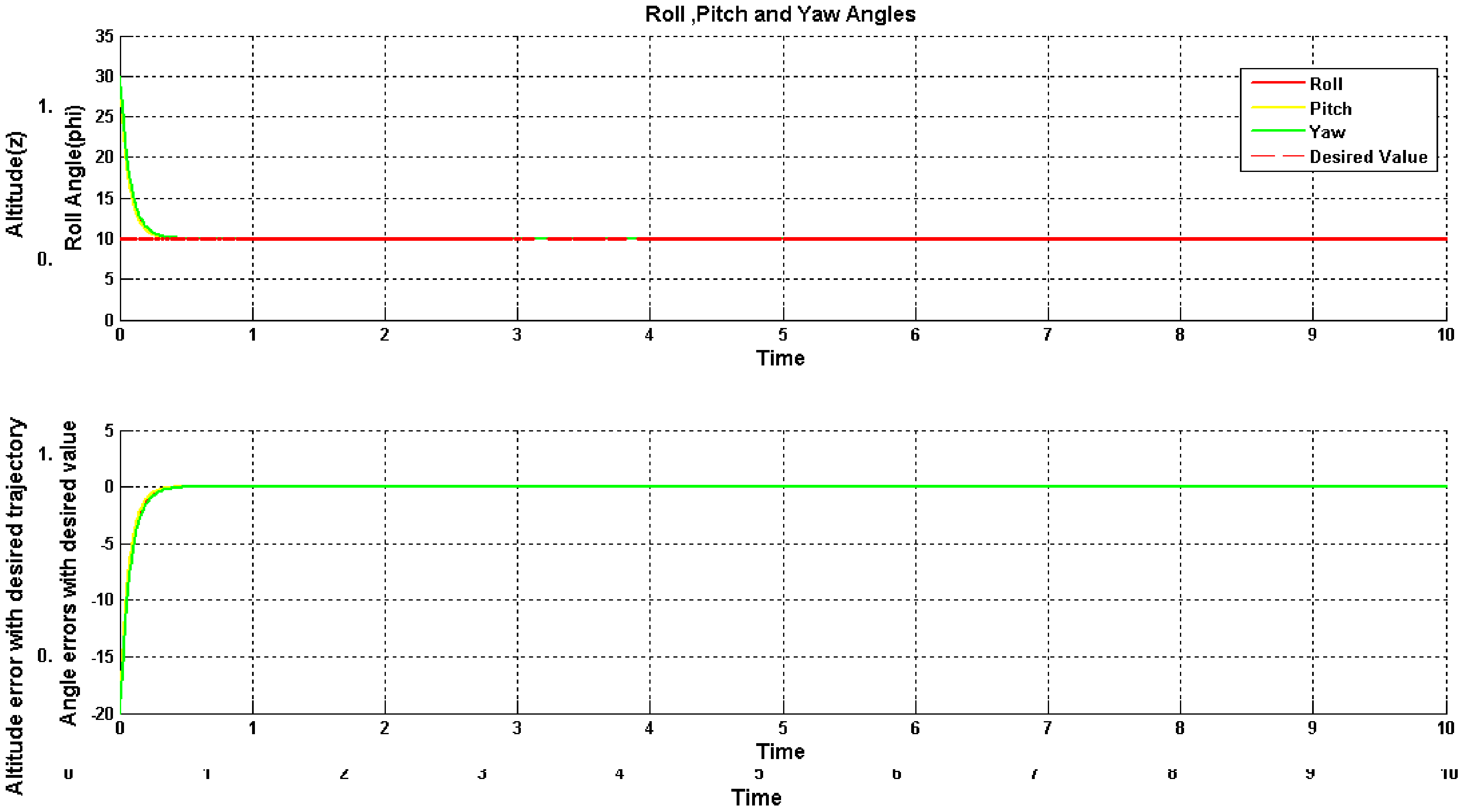
- Structure of the Controller

$$u(t) = -\beta k(t)[y(t) - y_{ref}(t)] + \delta$$

Adaptation Law

$$\dot{k}(t) = \begin{cases} \gamma (y(t) - y_{ref}(t))^p, if \ \left| y(t) - y_{ref}(t) \right| \ge \lambda \ ; (p \ge 1) \\ 0 \qquad , if \ \left| y(t) - y_{ref}(t) \right| \le \lambda \end{cases}$$

Simulation Results for λ – Tracking Method



Conclusion of Adaptive Control of Nonlinear System

- Advantages
  - Robustness against parameter uncertainties.
  - Rapid reconfiguration mechanism during fault occurrence.

- Disadvantages
  - Improper transient response
  - Inapplicable without any performance degradation mechanism

Linear System Modeling

- Jacobean matrix around the equilibrium point

$$z = 0 \qquad \psi = \frac{pi}{18} \qquad \theta = \frac{pi}{18} \qquad \phi = \frac{pi}{18}$$

$$\begin{bmatrix} \dot{z} \\ \ddot{z} \\ \dot{\phi} \\ \ddot{\phi} \\ \dot{\theta} \\ \ddot{\theta} \\ \dot{\psi} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} z \\ \dot{z} \\ \phi \\ \dot{\phi} \\ \theta \\ \dot{\theta} \\ \psi \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ g_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & g4 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}$$

$$y = \begin{bmatrix} z \\ \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} z \\ \dot{z} \\ \phi \\ \dot{\phi} \\ \theta \\ \dot{\theta} \\ \psi \\ \dot{\psi} \end{bmatrix}$$

$$g_1 = \frac{-2}{m} * b_1 \cos(\frac{pi}{18}) * \sin(\frac{pi}{18})$$

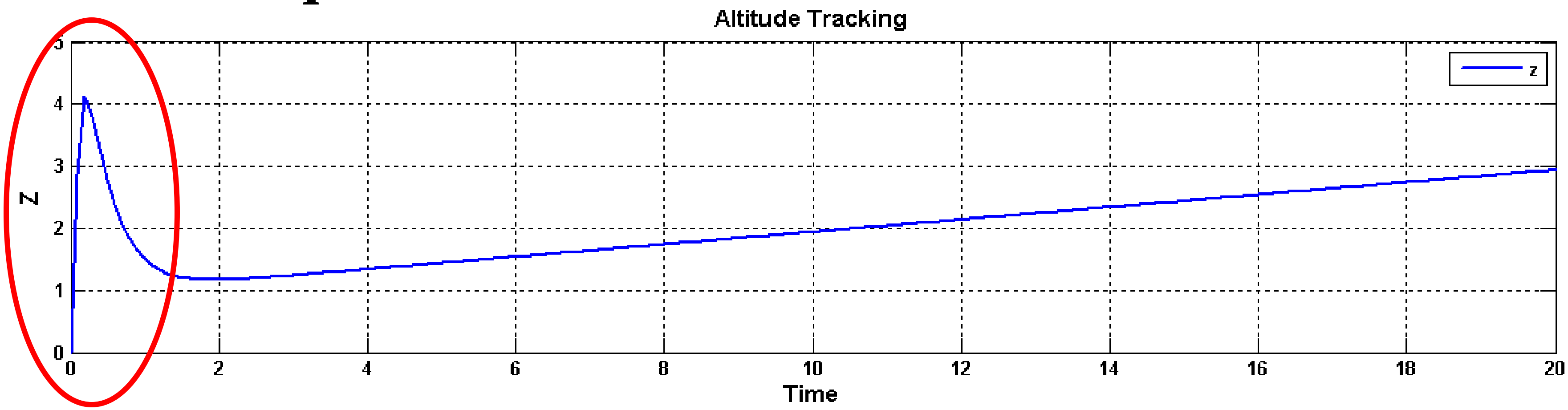
$$g_2 = \frac{l}{j_x} * b_2^*$$

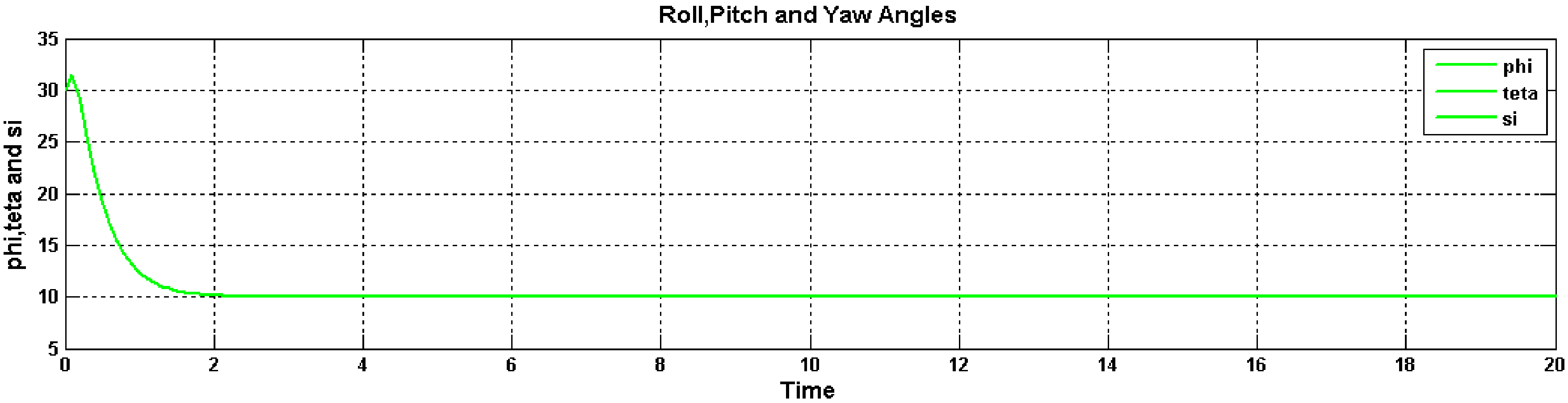
$$g_3 = \frac{b_3^* l}{J_y}$$

$$g_4 = \frac{b_4^* l}{J_z}$$

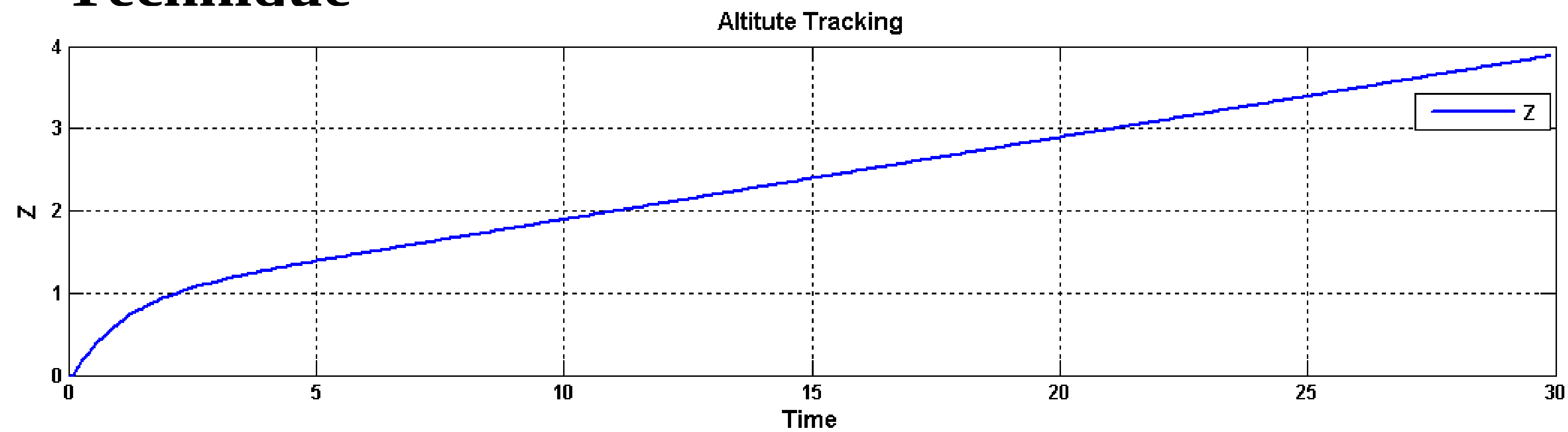
Controlling Mechanisms

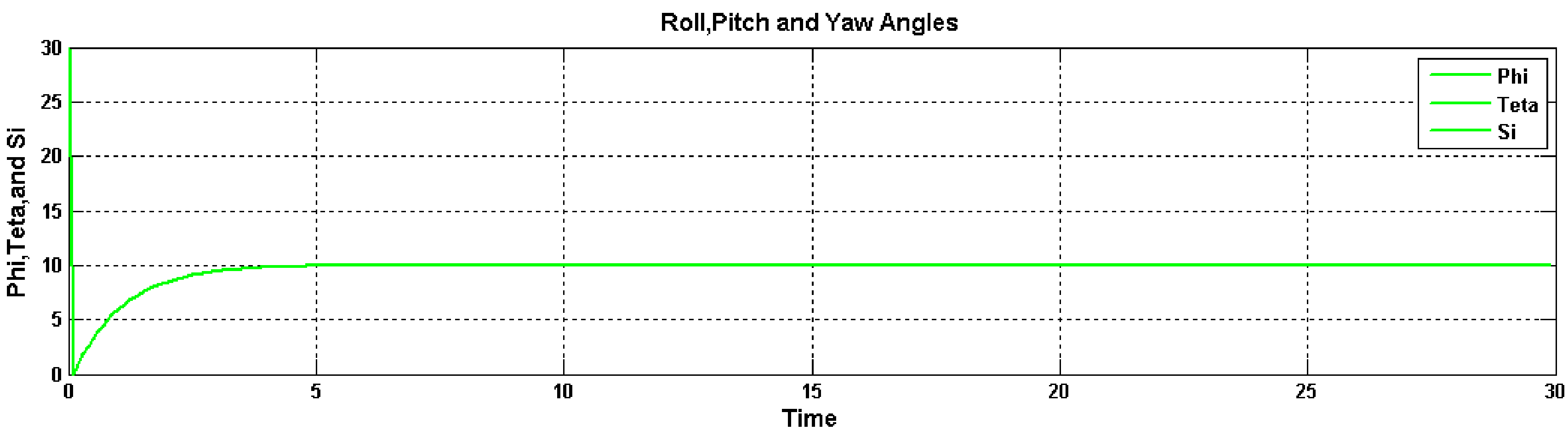
- **Linear Quadratic Regulator with Command Governor Technique**



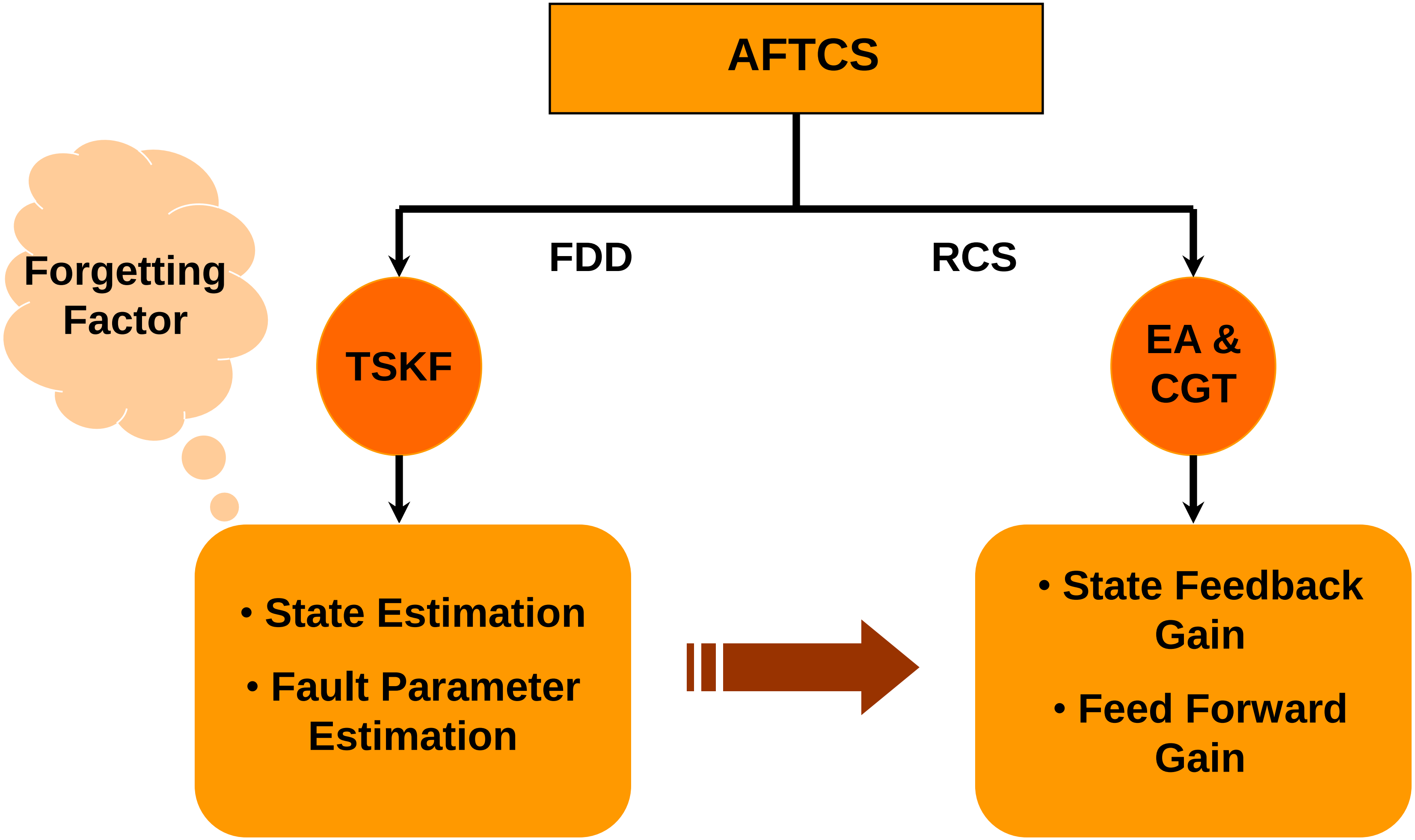


- **Eigen Structure Assignment with Command Governor Technique**

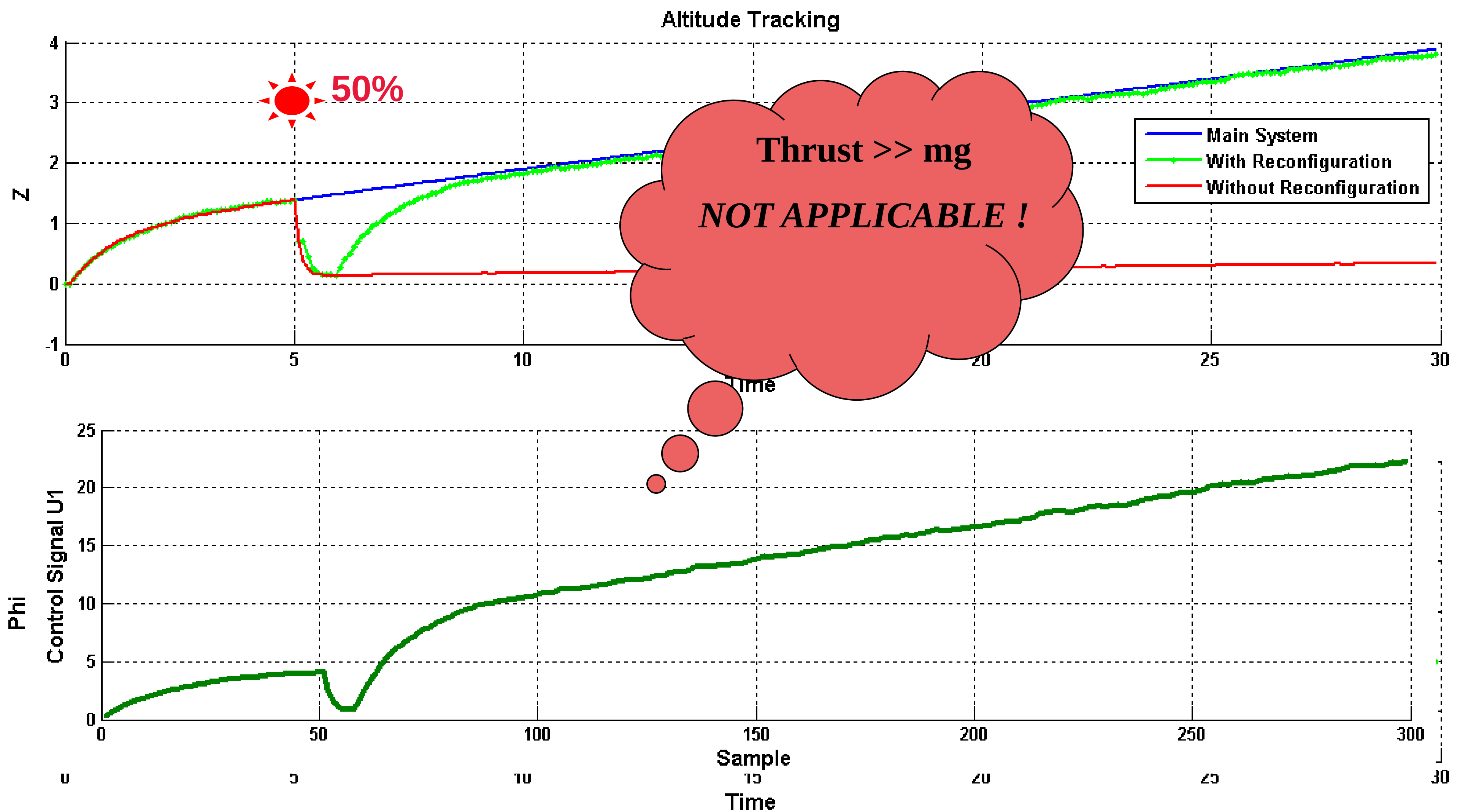




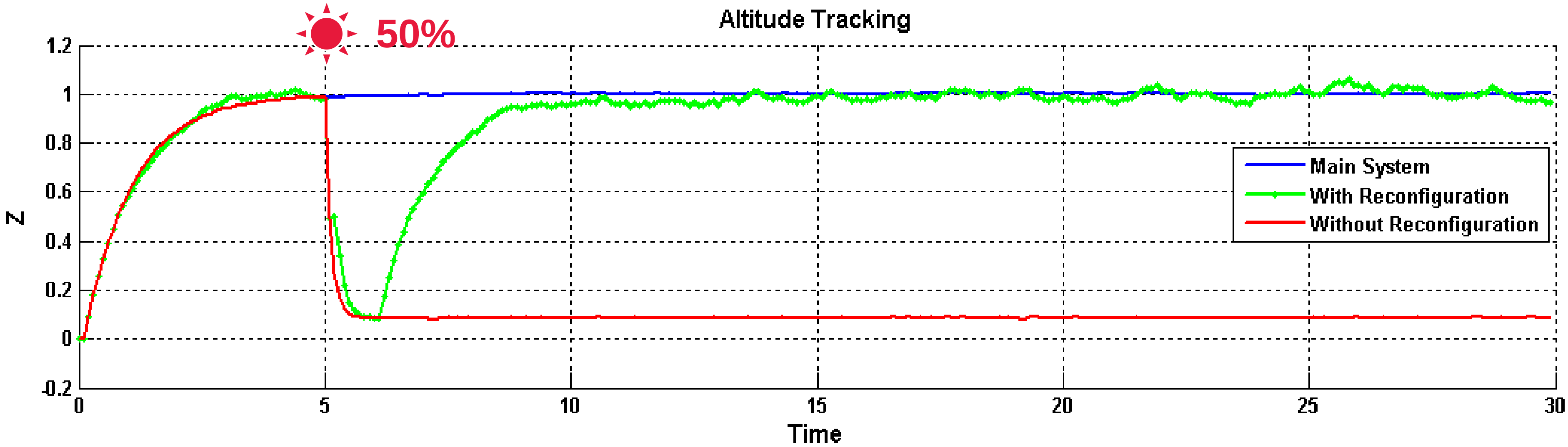
Active Fault Tolerant Control Approach for Linear System

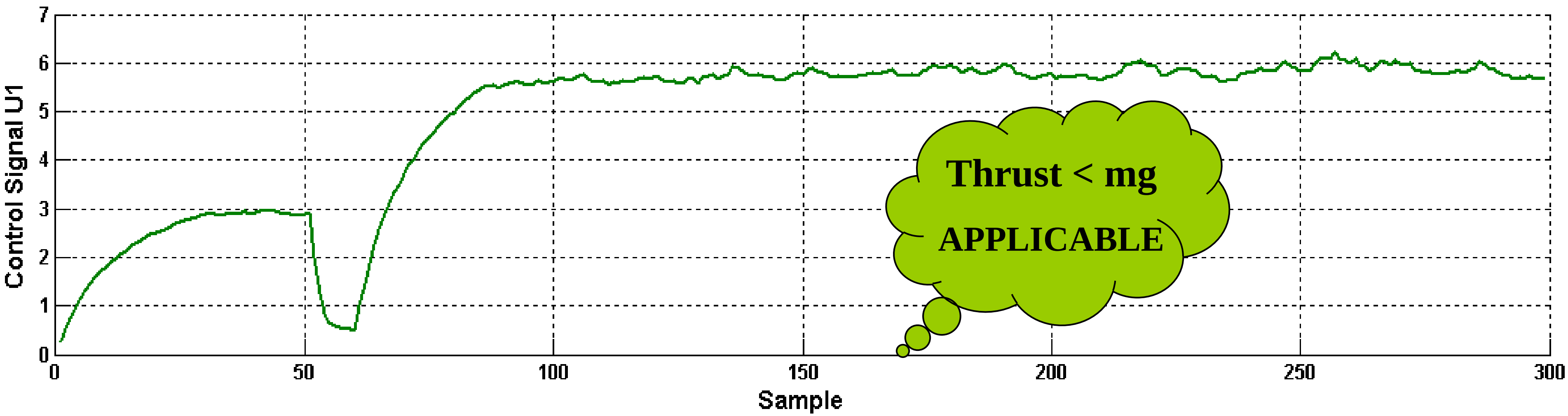


Variable Reference Input & 50% Actuator Fault

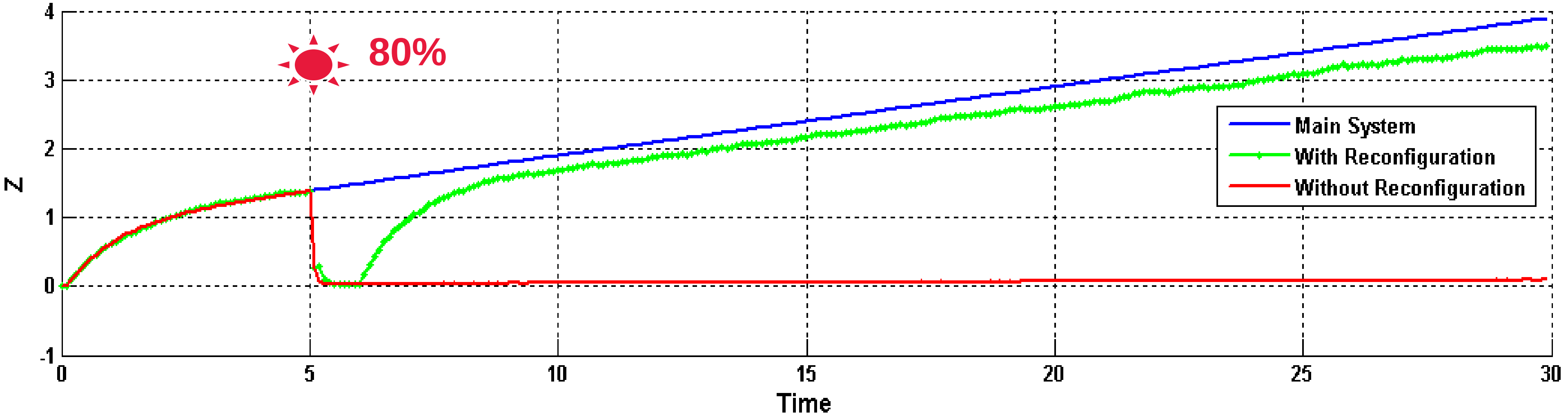


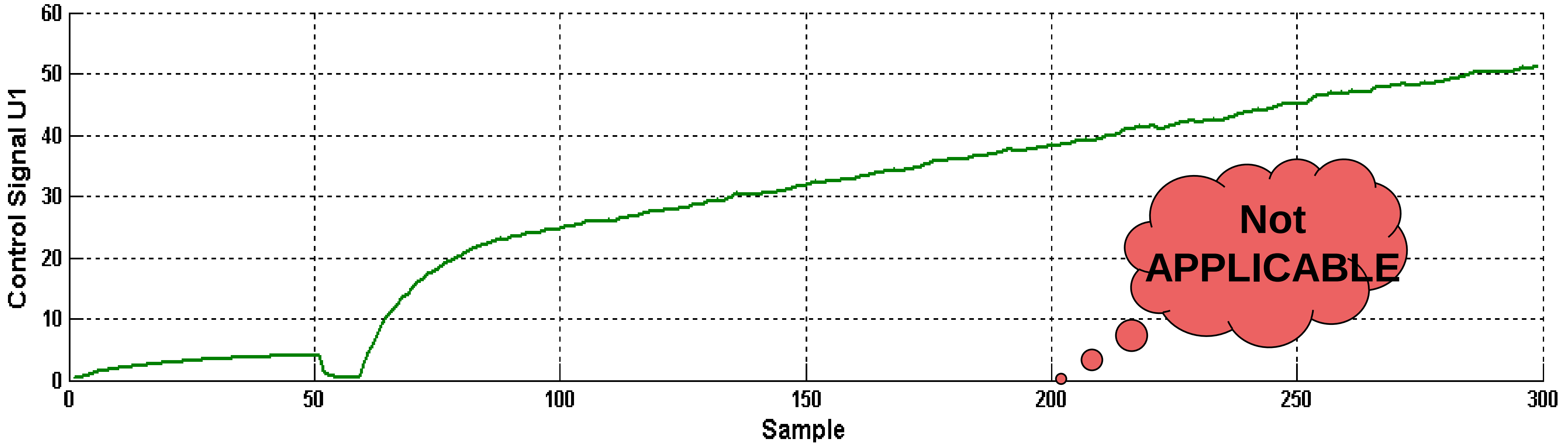
Constant Reference Input & 50% Actuator Fault



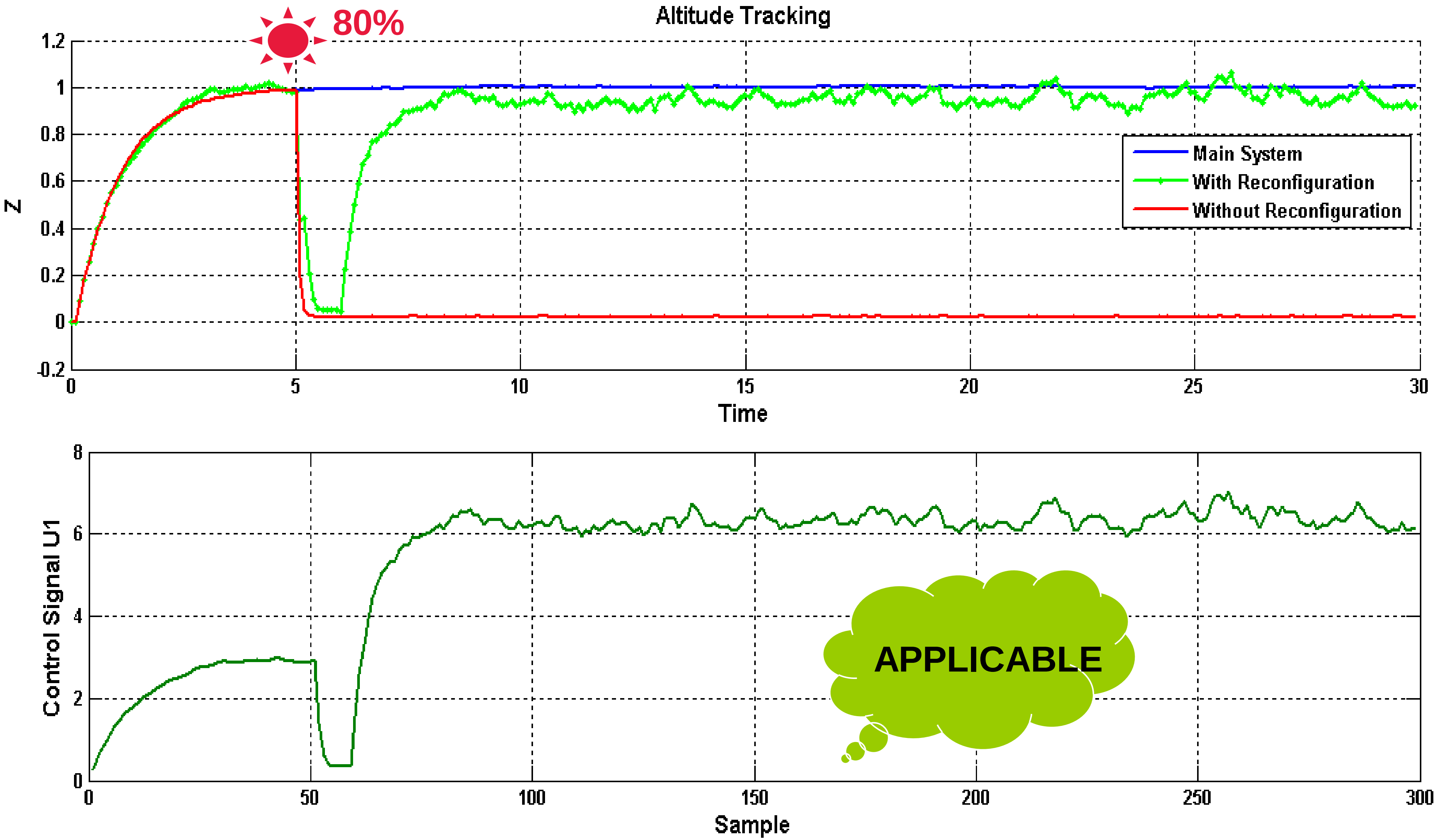


Variable Reference Input & 80% Actuator Fault





Constant Reference Input & 80% Actuator Fault



Conclusion

- Advantages
  - Acceptable transient response.
  - Applicable due to limited command control signals for constant reference input.
- Disadvantages
  - Slower reconfiguration mechanism
  - inapplicable for time varying reference input due to large command controlling signals.
- Suggestion for future work
  - Apply performance degradation mechanism for both linear and nonlinear model.