Model Reference Adaptive Fault/Damage Tolerant Control of Quadrotor Unmanned Aerial Vehicle (UAV)

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Outlines

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- **Modeling the Quad-Rotor UAV**
  - System model
- **Model Reference Adaptive Control (MRAC)**
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- **Simulation Results**
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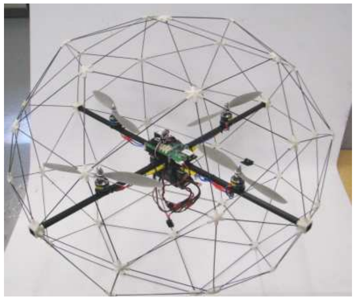
- **Experimental Results**
  - Nominal case
  - Fault Case:14.2% loss of the throttle and 15% of Propeller thrust
- **Conclusion**

Introduction



- The advantages of the quad-rotor UAV:
  - VTOL
  - Omni-directional flying
  - Does not require mechanical linkages to vary rotor angle of attack.
  - Can be protected by enclosing within a frame (Qball)
- MRAC controller advantages
  - The MRAC or MRAS is an important adaptive control methodology
  - Robustness to some changes of plant parameters and disturbance
  - Variety of applications: Aerospace, Chemical, Petrochemical, etc…

System Model

The Qball dynamics are :

$$
\begin{aligned}
\ddot{x} &= (\sin\psi \sin\phi + \cos\psi \sin\theta \cos\phi)\,\frac{U_1}{M} \quad &;& \quad \ddot{\phi} = \frac{U_2}{J_{xx}} \\
\ddot{y} &= (\sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi)\,\frac{U_1}{M} \quad &;& \quad \ddot{\theta} = \frac{U_3}{J_{yy}} \\
\ddot{z} &= -g + (\cos\theta \cos\phi)\,\frac{U_1}{M} \quad &;& \quad \ddot{\psi} = \frac{U_4}{J_{zz}}
\end{aligned}
\tag{1}
$$

with the relation between the force/moments U_i and the thrusts T_i is

$$
\begin{aligned}
U_1 &= T_1 + T_2 + T_3 + T_4 \\
U_2 &= L(T_3 - T_4) \\
U_3 &= L(T_1 - T_2) \\
U_4 &= K_{yaw}(u_1 + u_2 - u_3 - u_4)
\end{aligned}
\quad , \tag{2}
$$

and the brushless motor dynamics

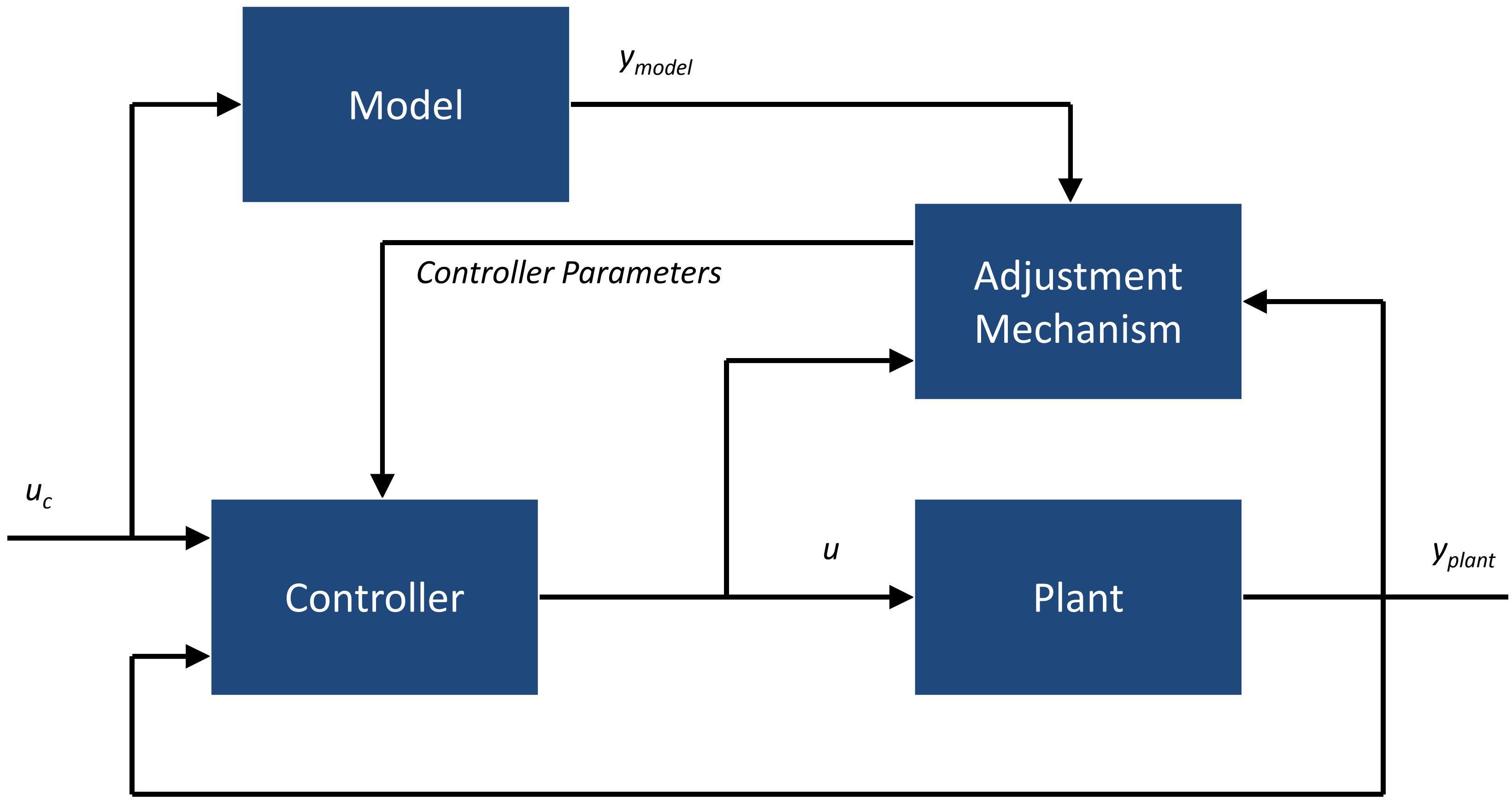
$$
T_i = K\frac{w}{s+w}u_i \tag{3}
$$

Different Adaptive Systems

Model-Reference Adaptive Systems

- The MIT rule
- Lyapunov stability theory
- Design of MRAS based on Lyapunov stability theory
- Hyperstability and passivity theory
- The error model
- Augmented error
- A model-following MRAS

MRAC Structure



Design controller to drive plant response to mimic ideal response (error = y_{plant}- y_{model} => 0)
Designer chooses: reference model, controller structure, and tuning gains for adjustment mechanism

The MIT rule

This MRAC approach has been developed around 1960 at MIT for aerospace applications. For illustration, consider the plant :

$$\ddot{y} = -a_1\dot{y} - a_2 y + u \tag{4}$$

where a_1 and a_2 are the unknown plant parameters. The reference model to be matched by the closed loop plant is :

$$\ddot{y}_m = -2\dot{y}_m - y_m + r \tag{5}$$

where r is the reference command. Let the control input u be defined as follows :

$$u = k_1\dot{y} + k_2 y + r \tag{6}$$

It is obvious that one can achieve perfect model following if k_1 and k_2 are chosen as :

$$k_1 = a_1 - 2 \text{ and } k_2 = a_2 - 1 \tag{7}$$

The MIT rule

- With $e = y - y_m$, adjust the parameters θ to minimize

$$J(\theta) = \frac{1}{2}e^2$$

- It is reasonable to adjust the parameters in the direction of the negative gradient of J:

$$\frac{d\theta}{dt} = -\gamma\frac{\partial J}{\partial\theta} = -\gamma e\frac{\partial e}{\partial\theta}$$

- $\partial e/\partial\theta$ is called the sensitivity derivative of the system and is evaluated under the assumption that θ varies slowly

The MIT rule

- The derivative of J is then described by

$$\frac{dJ}{dt} = e\frac{\partial e}{\partial t} = -\gamma e^2 \left(\frac{\partial e}{\partial \theta}\right)^2$$

- Alternatively, one may consider $J(e) = |e|$ in which case

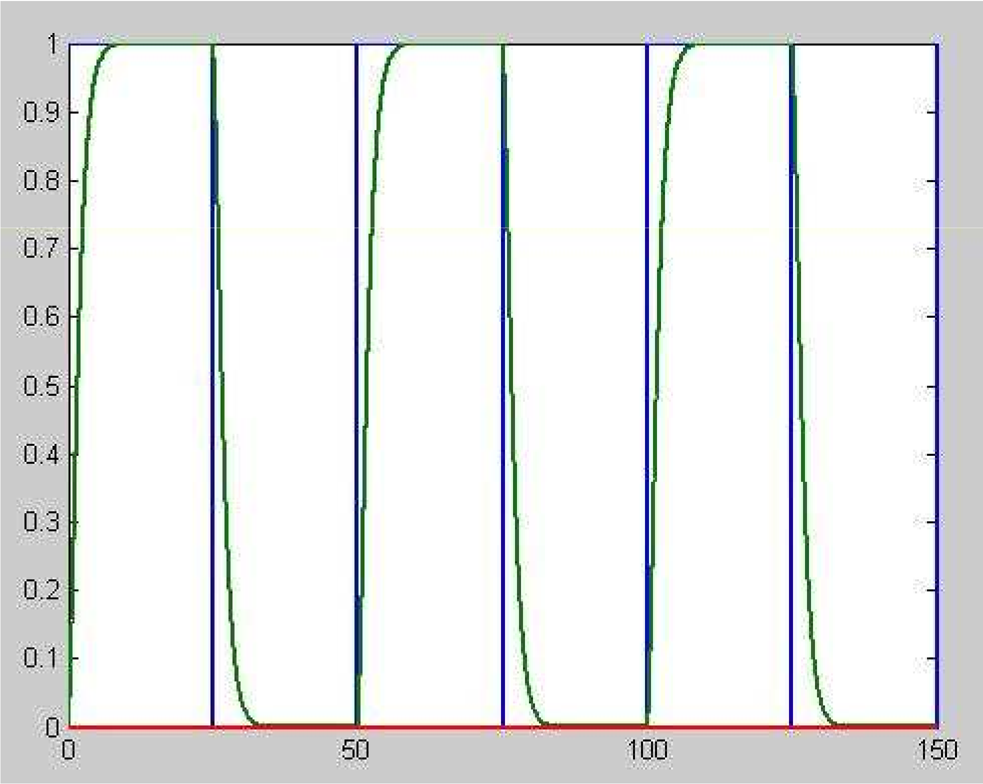
$$\frac{d\theta}{dt} = -\gamma\frac{\partial J}{\partial \theta} = -\gamma\frac{\partial e}{\partial \theta}\text{sign}(\text{e})$$

- The sign-sign algorithm used in telecommunications where simple implementation and fast computations are required, is

$$\frac{d\theta}{dt} = -\gamma\frac{\partial J}{\partial \theta} = -\gamma\text{sign}\left(\frac{\partial \text{e}}{\partial \theta}\right)\text{sign}(\text{e})$$

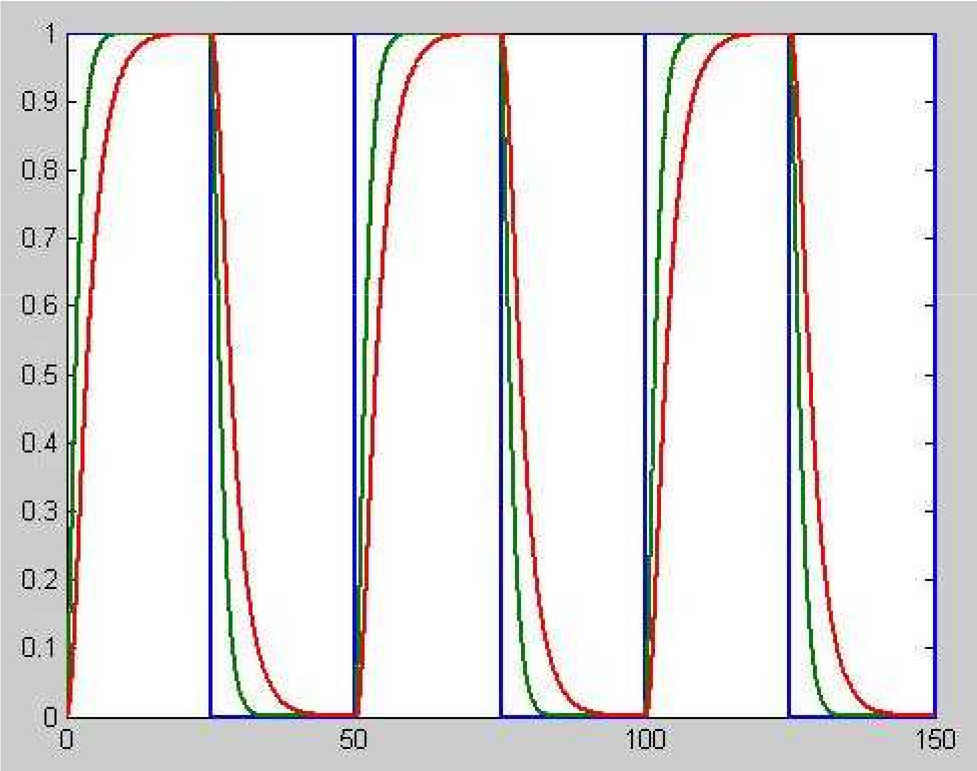
Simulation

MRAC and LQR both are set to zero



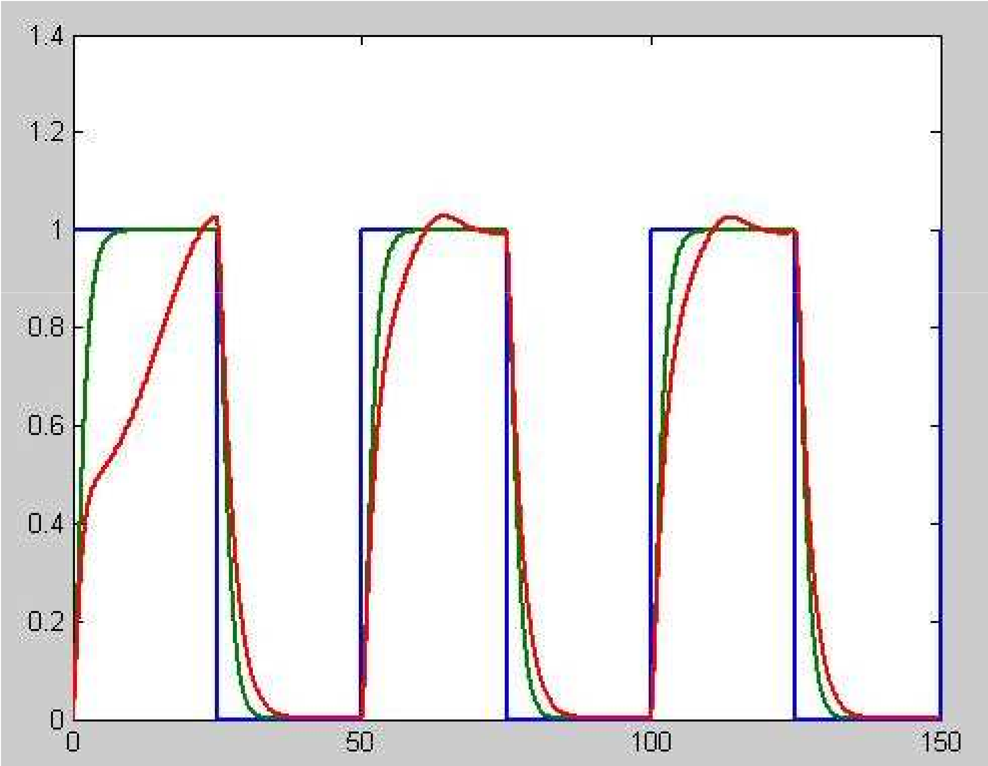
Simulation

MRAC is set to zero



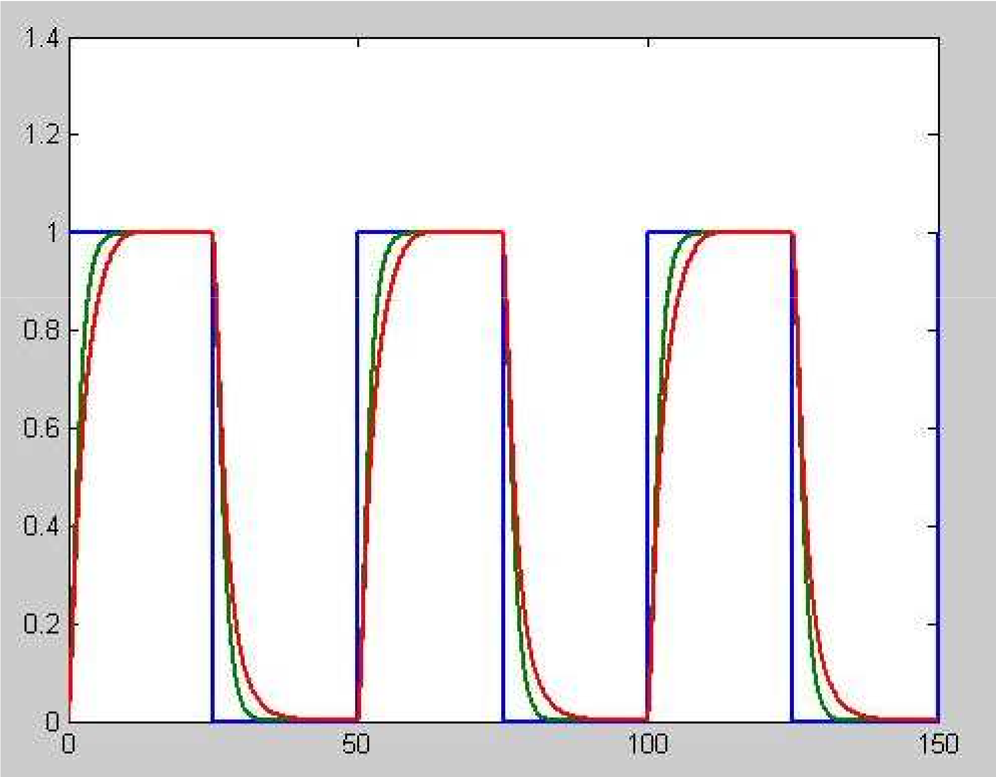
Simulation

LQR is set to zero



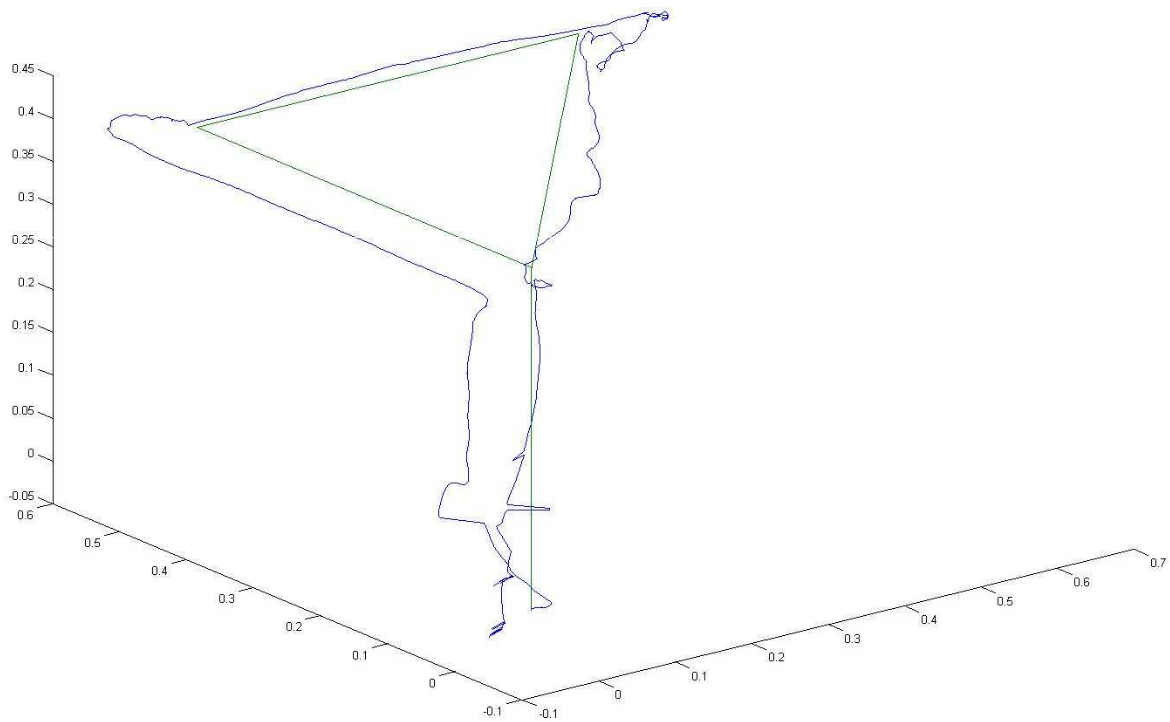
Simulation

MRAC+LQR



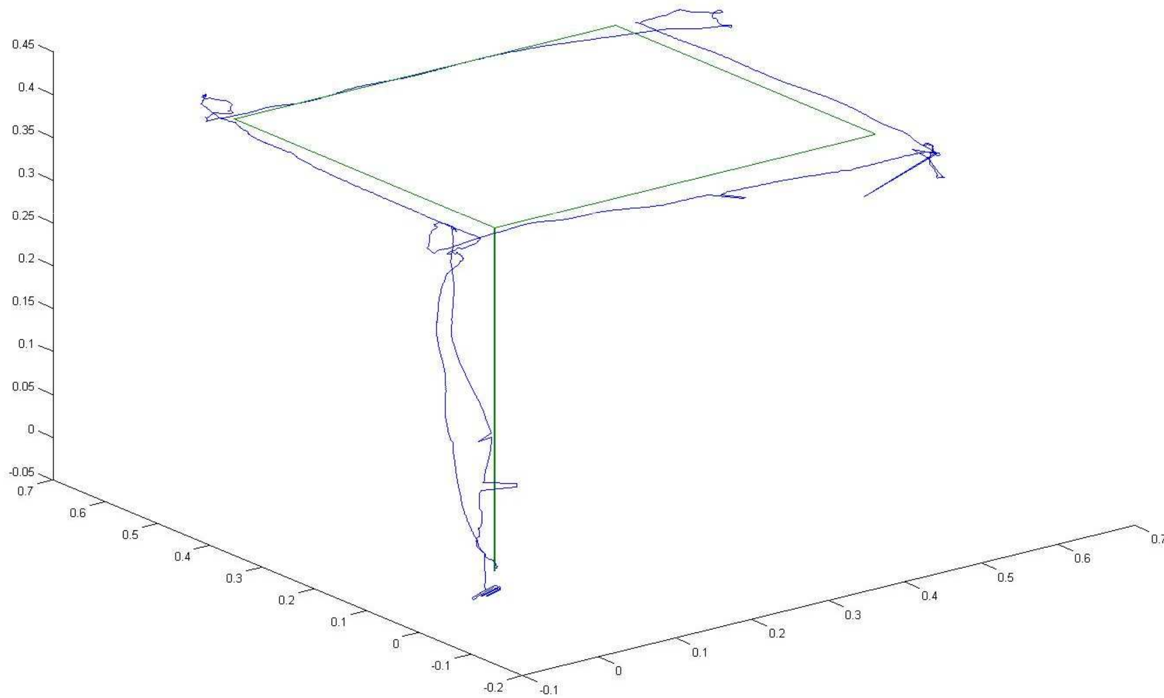
Fault-Free Implementation Result

Triangle trajectory tracking

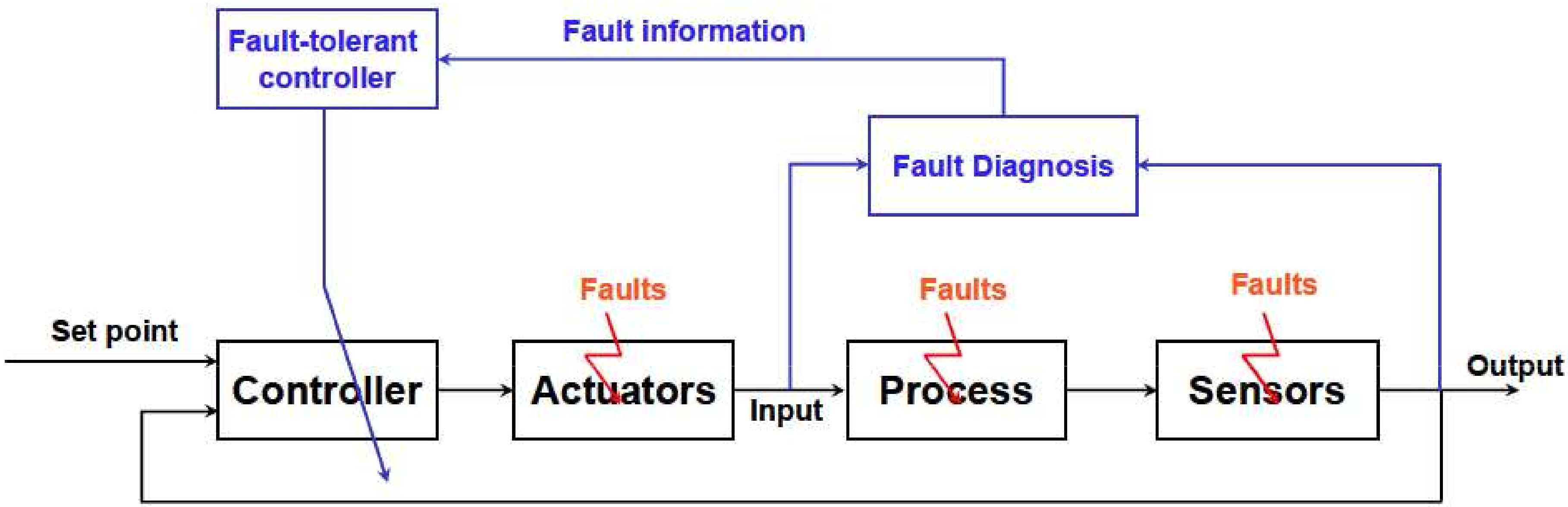


Fault-Free Implementation Result

Square trajectory tracking



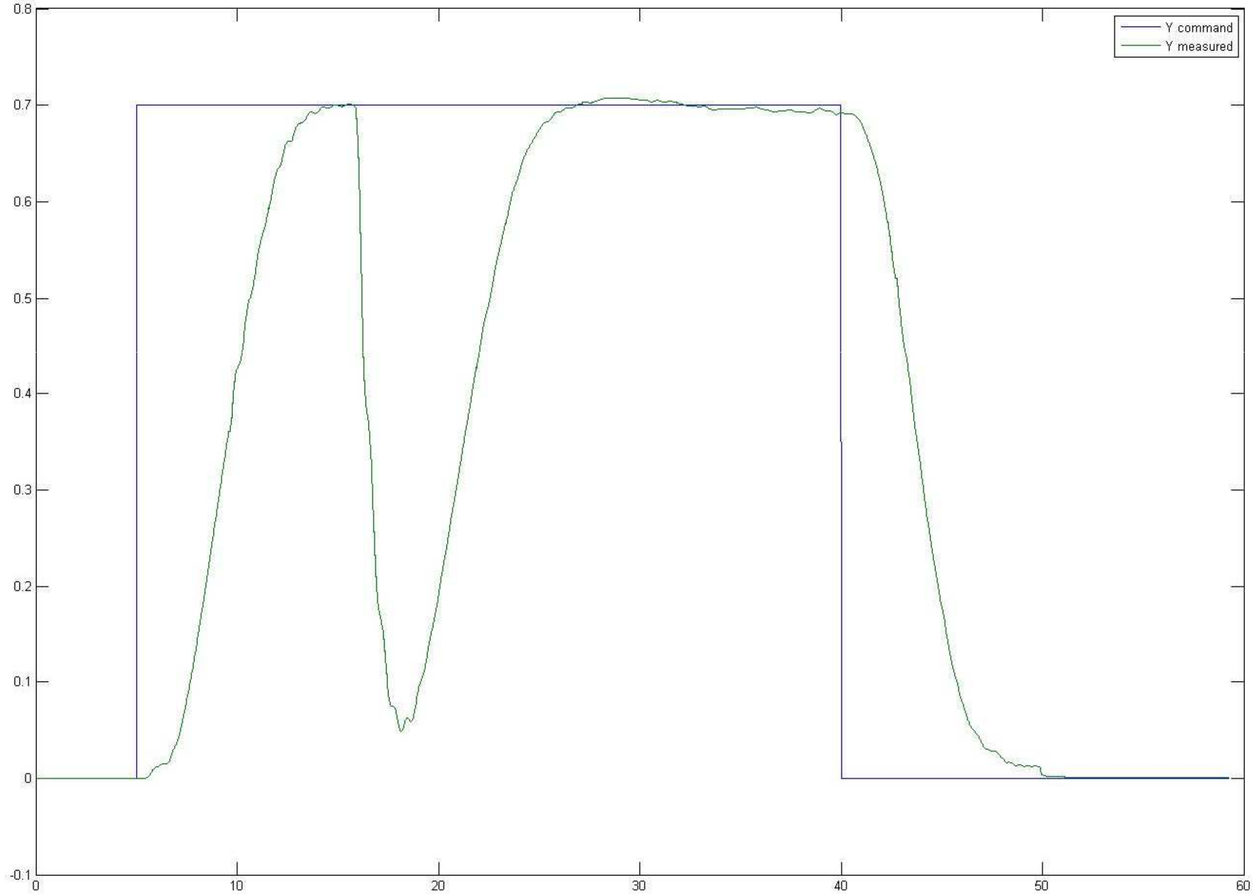
Fault Diagnosis and Fault-Tolerant Control



The fault diagnosis module detects, isolates and identifies the fault. The fault-tolerant control module accommodates the fault effect.

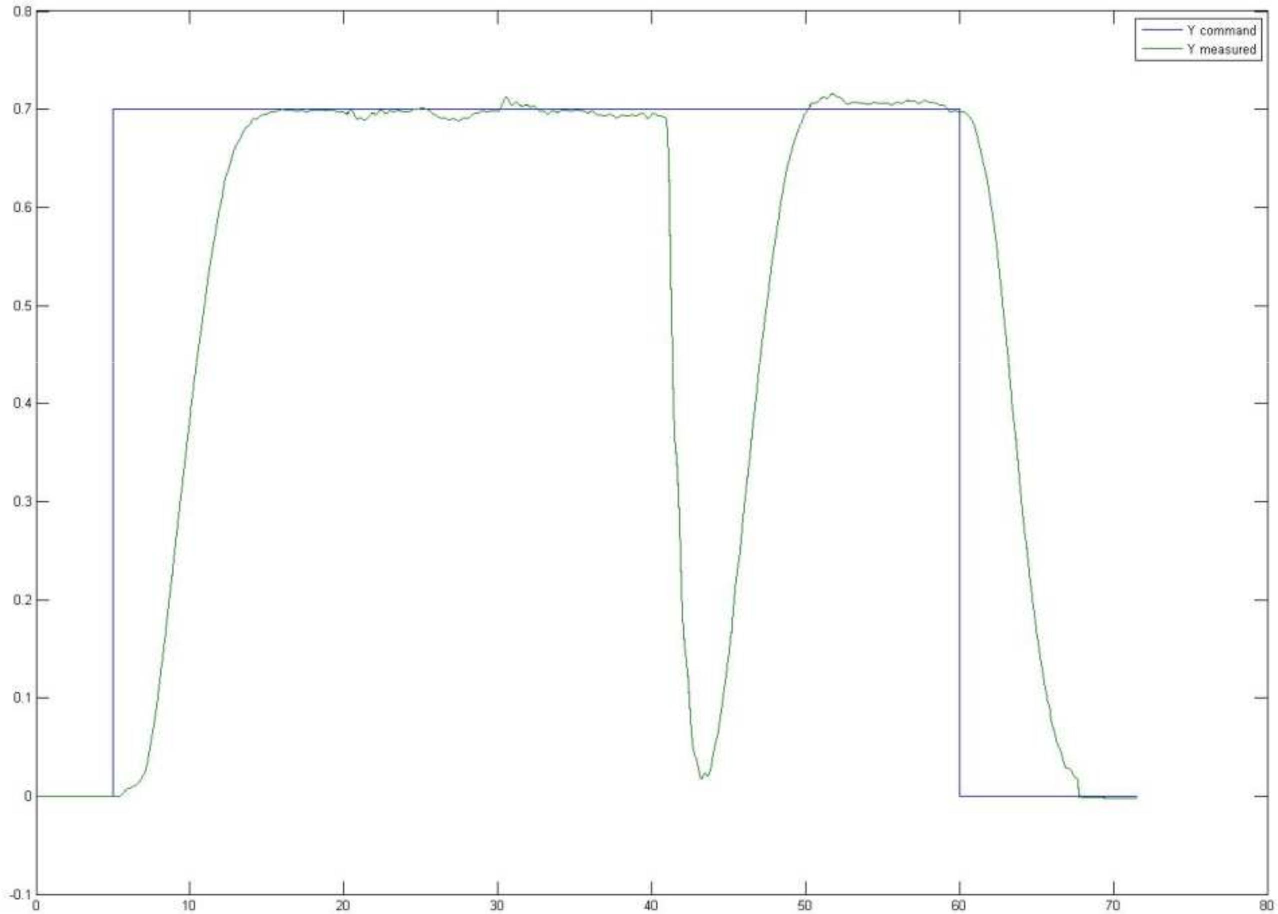
• Fault Injection (Implementation)

14.2 % of Fault in all actuators (Hovering mode 1)



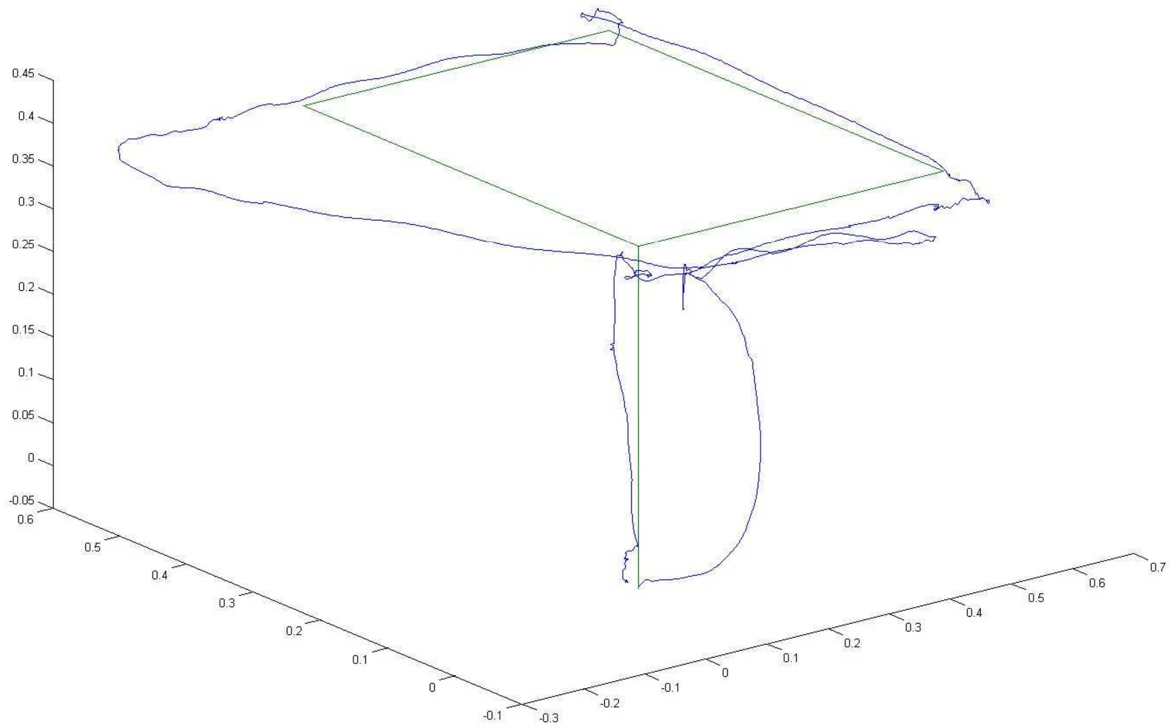
Fault Injection (Implementation)

14.2 % of Fault in all actuators (Hovering mode 2)



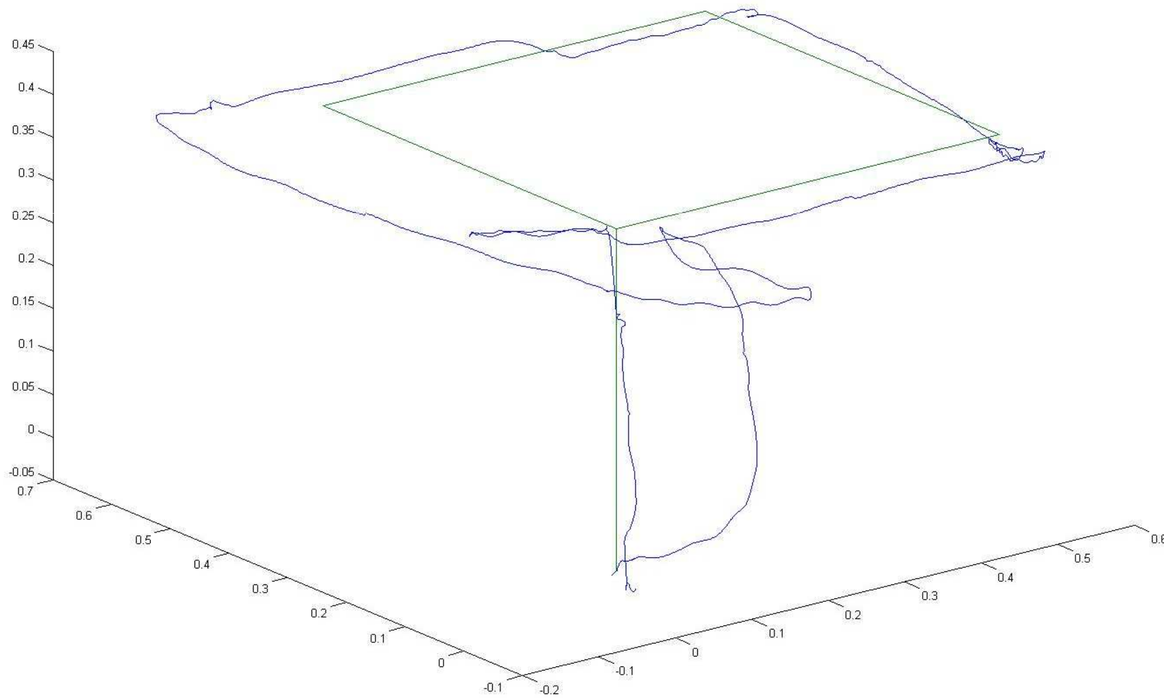
Fault Injection (Implementation)

Fault injection to back and left motor (Trajectory tracking mode 1)



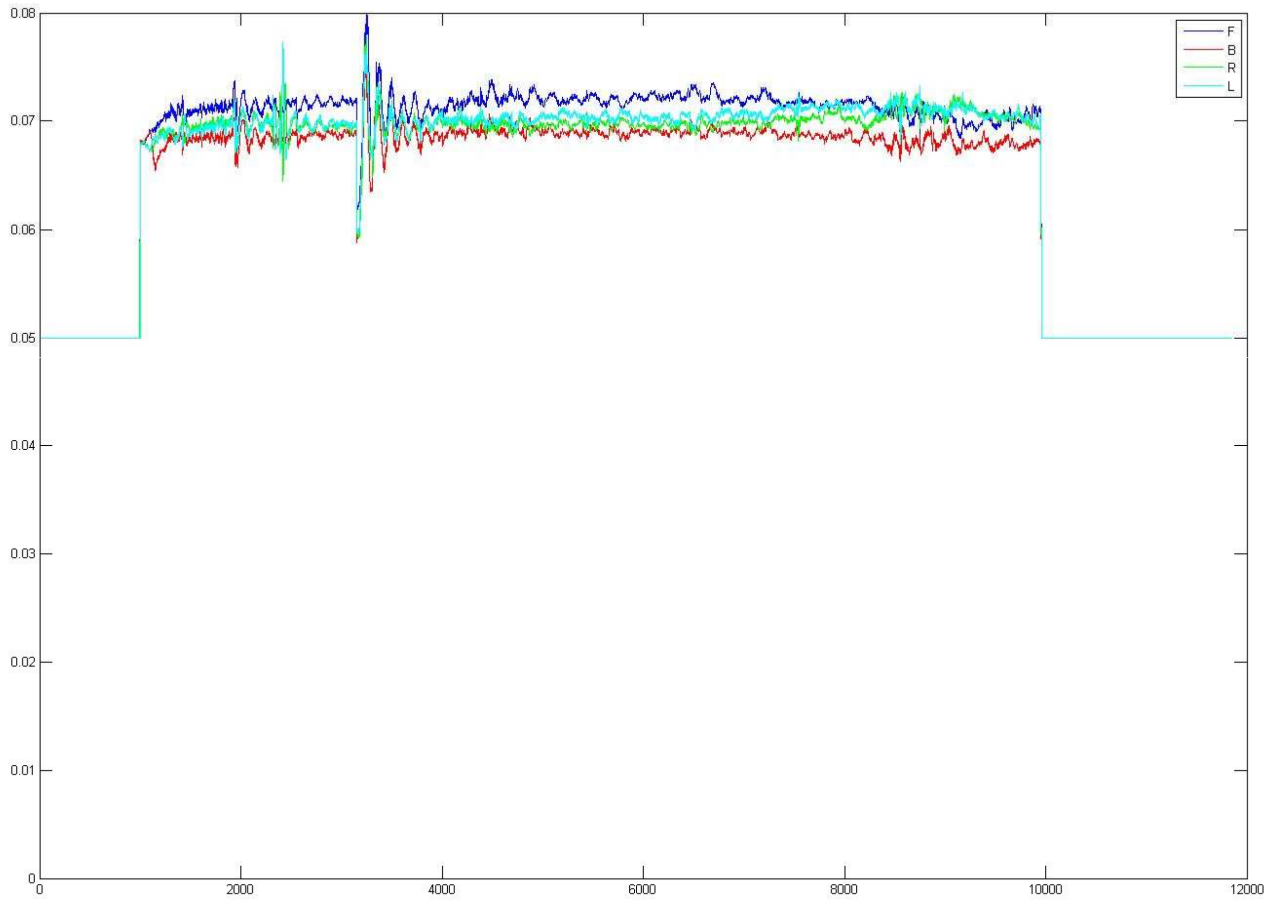
Fault Injection (Implementation)

Fault injection to back and left motor (Trajectory tracking mode 2)



Fault Injection (Implementation)

PWM Signals



Conclusions

1. Model Reference Adaptive Control forces the dynamic response of the controlled plant to approach asymptotically to that of reference model.
2. MRAC and LQR give the best performance to the system.
3. The model reference adaptive control minimize the effect of fault on the system's behaviour.
4. Better result can be obtained with higher adaption rates. However, very large adaption rate leads to system's instability.
5. Two types of fault (Throttle loss and propeller loss) showed almost the same result.

Thank you

Questions