IAA-AAS-DyCoSS2-10-02

AN APPLICATION OF ADAPTIVE FAULT-TOLERANT CONTROL TO NANO-SPACECRAFT

Yu Han,[*] James Biggs,[†] and Naigang Cui[*]

Since nano-spacecraft are small, low cost and do not undergo the same rigor of testing as conventional spacecraft, they have a greater risk of failure. In this paper we address the problem of attitude control of a nano-spacecraft that experiences different types of faults. Based on the traditional quaternion feedback control method, an adaptive fault-tolerant control method is developed, which can ensure that the control system still operates when the actuator fault happens. This paper derives the fault-tolerant control logic under both actuator gain fault mode and actuator deviation fault mode. Taking the parameters of the UKube-1 in the simulation model, a comparison between a traditional spacecraft control method and the adaptive fault-tolerant control method in the presence of a fault is undertaken. It is shown that the proposed controller copes with faults and is able to complete an effective attitude control maneuver in the presence of a fault.

INTRODUCTION

The next generation nano-spacecraft have the potential to perform applications that are conventionally undertaken with expensive multi-ton spacecraft. Nano-spacecraft have a mass between 1 and 10 kg and offer the opportunity of access to space at a reduced cost. Furthermore, nano-spacecraft can enable missions that a larger spacecraft cannot accomplish, such as: constellations for low data rate communication, using formations to gather data from multiple points, in-orbit inspection of larger spacecraft and university related research.

Many nano-spacecraft have been launched and the majority of the attitude control systems incorporate magnetic actuation as a means to de-tumble the spacecraft. Currently fine pointing of nano-spacecraft is being achieved with the use of methods such as quaternion feedback control[1] and advances in nano-reaction wheel technology. However, nano-spacecraft, in general, do not undergo the rigorous testing that is required for multi-tonne spacecraft. After all the incentive to develop nano-spacecraft is to have low cost access to space balanced with an increase in risk of failure. Therefore, nano-spacecraft are more susceptible to faults and it is important that the spacecraft can adapt to these faults if and when they occur. Moreover, the electric system, propulsion system and actuators of nano-spacecraft are simple and cheap relative to conventional subsystems, but this is at the cost of an increase in the probability of a fault occurring. In particular,

[*] School of Astronautics, Harbin Institute of Technology, Mailbox 345, Harbin Institute of Technology, 92 Xidazhi Street, Harbin, China
[†] Advanced Space Concepts Laboratory, University of Strathclyde, Mechanical and Aerospace Engineering, James Weir Building, 75 Montrose Street, Glasgow, UK, G1 1XJ

the control system of nano-spacecraft needs to be fault tolerant, while maintaining a low-cost in production. This paper addresses this problem by developing an adaptive fault-tolerant attitude control method that is suitable for nano-spacecraft and which is simple to implement.

The adaptive fault-tolerant control[2,3] method in this paper can effectively ensure that the attitude control system still operates when the actuator fault[4,5,6] occurs. When a malfunction occurs, the control law can respond by adaptive restructuring. The adaptive fault-tolerant control method, presented here, is a modification of the traditional quaternion feedback control law. The method uses a reference model to calculate the ideal systems state. Through comparing the ideal system state to the actual system state, the system can identify when a fault occurs. An adaptive parameter is added, which is based on the bias of the actual data and the desired data. Hence, the system accelerates the control feedback input when the bias exists. Furthermore, the control method is simple to implement with low-computational requirement that could be suitable for implementation on a real nano-spacecraft.

Several fault modes of the actuator[7] are considered such as gain and deviation. Gain[8] means that the actuator loses partial power with random-variation in its health level. Deviation means that the actuator is delivering a constant torque above or below the required torque. In addition, previous literatures on fault-tolerant control methods only address one fault mode at a time. However, due to the high-risk nature of nano-spacecraft the attitude control should be able to adapt to a situation where more than one fault can occur. The method in this paper is suitable for both fault modes of gain and deviation.

A simulation is undertaken of a nano-spacecraft to demonstrate the effectiveness of the control method in the presence of faults. UKube-1[*] is a typical example of a nano-spacecraft, whose dimensions are 10cm×10cm×30cm and weighs about 3kg. A comparison between traditional spacecraft control methods and the adaptive fault-tolerant control method in the presence of faults is undertaken. It is shown that the proposed controller copes with faults and is able to complete an effective attitude control maneuver, whereas, a conventional controller fails to do so.

SPACECRAFT MODELS AND TRADITIONAL QUATERNION FEEDBACK CONTROL LOGIC

In the case of a nano-spacecraft, such as the UKube-1, the dynamics can be modeled as a rigid body with negligible moving parts and no liquid propellant. This section describes the general equations for the attitude kinematics and dynamics of the spacecraft and the traditional quaternion feedback control logic.

Attitude Kinematics and Dynamics

The Radial-Transverse-Normal (RTN) reference frame used to describe the orbit of the spacecraft. In this reference frame $\hat{\boldsymbol{R}}$ is parallel with the radial vector, $\hat{\boldsymbol{N}}$ is parallel with the orbit normal and $\hat{\boldsymbol{T}}$ completes the orthonormal frame.[9,10]

The other important reference frame is the body-fixed reference frame with basis vectors $\left\{\hat{\boldsymbol{i}}, \hat{\boldsymbol{j}}, \hat{\boldsymbol{k}}\right\}$. The spacecraft attitude is then defined as the relative angle from the local-level coordinates to the body frame.

Euler's rotational equations of motion for a rigid spacecraft are defined as[11]:

---

[*] http://www.bis.gov.uk/ukspaceagency/missions/ukube-pilot-programme

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^{\times}\boldsymbol{J}\boldsymbol{\omega} + \boldsymbol{u} \tag{1}$$

where $\boldsymbol{J} \in \mathbb{R}^{3\times3}$ denotes the matrix of inertia matrix of the spacecraft; $\boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3]^T$ the angular velocities of the spacecraft body frame with respect to the inertial frame; $\boldsymbol{u} = [u_1, u_2, u_3]^T$ the control torque input vector. The matrix notation $\boldsymbol{\omega}^{\times}$ is recorded as

$$\boldsymbol{\omega}^{\times} \equiv \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \tag{2}$$

The attitude kinematics of the spacecraft can be parameterised using quaternions:

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{3}$$

where $[q_1 \quad q_2 \quad q_3 \quad q_4]^T$ denotes the quaternions which represent the attitude of the spacecraft in the body frame with respect to the inertial frame, which must satisfy the constraint

$$q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1 \tag{4}$$

We take $\boldsymbol{q} = (q_1, q_2, q_3)$. The rotation matrix that brings the inertial frame to the body frame, denoted by $R(\boldsymbol{q}) \in SO(3)$, is defined as follows:

$$R \triangleq \left(q_4^2 - \boldsymbol{q}^T\boldsymbol{q}\right)\boldsymbol{I}_3 + 2\boldsymbol{q}\boldsymbol{q}^T - 2q_4\boldsymbol{q}^{\times} \tag{5}$$

where I_3 is the 3×3 identity matrix, and the angular velocity of body frame with respect to inertial frame expressed in body frame, denoted by $\boldsymbol{\omega}(t)$, can be computed from equation (3) as follows[12]:

$$\boldsymbol{\omega} = 2\left(q_4\dot{\boldsymbol{q}} - \boldsymbol{q}\dot{q}_4\right) - 2\boldsymbol{q}^{\times}\dot{\boldsymbol{q}} \tag{6}$$

Traditional Quaternion Feedback Control Logic

In this study the adaptive control requires a model of the system dynamics and it is essential that this can be numerically integrated without the problem of singularities encountered when using Euler angles. Therefore, quaternions are used as they offer a global parameterization of the rotation of a spacecraft. A traditional quaternion feedback controller is used chosen due to its simplicity and ease of gain tuning, and used as a benchmark to test against the adaptive control. The control torque $\boldsymbol{u}$ of spacecraft system, equation (1) is equated to:

$$\boldsymbol{u} = -\boldsymbol{K}\boldsymbol{q}_e - \boldsymbol{C}\boldsymbol{\omega}_e \tag{7}$$

Where $\boldsymbol{K} = k\boldsymbol{J}$ and $\boldsymbol{C} = c\boldsymbol{J}$ are constant gain matrices[1,13]. The gains are multiplied by the inertia matrix so that the gains are proportionally higher on the axes with higher moments of inertia. The angular velocity error is given by $\boldsymbol{\omega}_e = \boldsymbol{\omega} - \boldsymbol{\omega}_c$, and the quaternion error by

$$\begin{bmatrix} q_{1e} \\ q_{2e} \\ q_{3e} \\ q_{4e} \end{bmatrix} = \begin{bmatrix} q_{4c} & q_{3c} & -q_{2c} & -q_{1c} \\ -q_{3c} & q_{4c} & q_{1c} & -q_{2c} \\ q_{2c} & -q_{1c} & q_{4c} & -q_{3c} \\ q_{1c} & q_{2c} & q_{3c} & q_{4c} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{8}$$

If the commanded attitude angular velocity vector and quaternion vector is simply the origin $\boldsymbol{\omega}_c = (0,0,0)$ and $(q_{1c}, q_{2c}, q_{3c}, q_{4c}) = (0,0,0,+1)$, then the control logic, equation (7), becomes

$$\boldsymbol{u} = -\boldsymbol{Kq} - \boldsymbol{C\omega} \tag{9}$$

Spacecraft Model

We primarily focus on the spacecraft based on the UKube-1, assuming of which is axisymmetric. If we assuming that the principal inertias is written as

$$\boldsymbol{J} = \begin{bmatrix} J_{11} & 0 & 0 \\ 0 & J_{22} & 0 \\ 0 & 0 & J_{33} \end{bmatrix} \tag{10}$$

Table 1 shows the properties of the spacecraft. [14]

Table 1. Physical Properties of Spacecraft

Principal inertias of spacecraft	$J_{11} = 0.0109 kgm^2$ $J_{22} = J_{33} = J_s = 0.05 kgm^2$
Drag coefficient	$C_d = 3$
Reflectivity	$\rho = 0.6$
Residual dipole in z-body axis	$M_{rz} = 10 \times 10^{-3} Am^2$
Maximum reaction wheel torque	$N_m = 1 \times 10^{-3} Nm$

ADAPTIVE FAULT-TOLERANT CONTROL LOGIC

In this section control logic equations for the torque-free attitude motion of axisymmetric spacecraft are derived using adaptive-tolerant control logic. Through adding a reference model, the movement status of spacecraft can be monitored at any time. The control logic equations under actuator gain fault and actuator deviation fault situations is shown in this section. There also exists the control torque limit in each actuator.

The Adaptive Control Logic without Fault

The adaptive control logic should continuously detect if there is any difference between the ideal model of the system state under control and the actual state of the system. If a fault occurs there will be a difference between the state of the ideal system and the actual system. In contrast to classical proportional controllers that track a reference trajectory or desired steady state, the adaptive controller tracks the state of an idealized system under normal operating condition[15,16]. The ideal reference model operating under normal conditions can be expressed as

$$\boldsymbol{J}\dot{\hat{\boldsymbol{\omega}}} + \hat{\boldsymbol{\omega}}^{\times}\boldsymbol{J}\hat{\boldsymbol{\omega}} = \boldsymbol{\tau}$$
$$\begin{bmatrix} \dot{\hat{q}}_1 \\ \dot{\hat{q}}_2 \\ \dot{\hat{q}}_3 \\ \dot{\hat{q}}_4 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & \hat{\omega}_3 & -\hat{\omega}_2 & \hat{\omega}_1 \\ -\hat{\omega}_3 & 0 & \hat{\omega}_1 & \hat{\omega}_2 \\ \hat{\omega}_2 & -\hat{\omega}_1 & 0 & \hat{\omega}_3 \\ -\hat{\omega}_1 & -\hat{\omega}_2 & -\hat{\omega}_3 & 0 \end{bmatrix}\begin{bmatrix} \hat{q}_1 \\ \hat{q}_2 \\ \hat{q}_3 \\ \hat{q}_4 \end{bmatrix} \tag{11}$$

where $\hat{\boldsymbol{\omega}} = (\hat{\omega}_1, \hat{\omega}_2, \hat{\omega}_3)$ is the angular velocity of reference model, $(\hat{q}_1, \hat{q}_2, \hat{q}_3, \hat{q}_4)$ represents the quaternion vector and $\boldsymbol{\tau}$ is the control torque input vector. We take $\hat{\boldsymbol{q}} = (\hat{q}_1, \hat{q}_2, \hat{q}_3)$.

The control torque $\boldsymbol{\tau}$ of the reference model, equation (11), which is based on the control logic of traditional quaternion feedback control logic, as equation (7), is shown as

$$\boldsymbol{\tau} = -\boldsymbol{K}\hat{\boldsymbol{q}}_e - \boldsymbol{C}\hat{\boldsymbol{\omega}}_e \tag{12}$$

where $\boldsymbol{K} = k\boldsymbol{J}$ and $\boldsymbol{C} = c\boldsymbol{J}$ are the same as those in equation (7). The angular velocity of reference model is given by $\hat{\boldsymbol{\omega}}_e = \hat{\boldsymbol{\omega}} - \hat{\boldsymbol{\omega}}_c$, and the quaternion error of reference model is

$$\begin{bmatrix} \hat{q}_{1e} \\ \hat{q}_{2e} \\ \hat{q}_{3e} \\ \hat{q}_{4e} \end{bmatrix} = \begin{bmatrix} \hat{q}_{4c} & \hat{q}_{3c} & -\hat{q}_{2c} & -\hat{q}_{1c} \\ -\hat{q}_{3c} & \hat{q}_{4c} & \hat{q}_{1c} & -\hat{q}_{2c} \\ \hat{q}_{2c} & -\hat{q}_{1c} & \hat{q}_{4c} & -\hat{q}_{3c} \\ \hat{q}_{1c} & \hat{q}_{2c} & \hat{q}_{3c} & \hat{q}_{4c} \end{bmatrix}\begin{bmatrix} \hat{q}_1 \\ \hat{q}_2 \\ \hat{q}_3 \\ \hat{q}_4 \end{bmatrix} \tag{13}$$

If the commanded attitude angular velocity vector and quaternion vector is simply the origin separately defined as $\hat{\boldsymbol{\omega}}_c = (0,0,0)$ and $(\hat{q}_{1c}, \hat{q}_{2c}, \hat{q}_{3c}, \hat{q}_{4c}) = (0,0,0,+1)$, then the control logic (12) becomes

$$\boldsymbol{\tau} = -\boldsymbol{K}\hat{\boldsymbol{q}} - \boldsymbol{C}\hat{\boldsymbol{\omega}} \tag{14}$$

In this actual system, the control logic of a quaternion feedback control tracks the reference model. The angular velocity vector and the quaternion trace of the current system separately are $\hat{\boldsymbol{\omega}}$ and $\hat{\boldsymbol{q}}$. The error vector of angular velocity is defined as the difference between the current angular velocity and orientation of the system and the angular velocity and orientation of the ideal reference model as $\boldsymbol{e}_\omega = \boldsymbol{\omega} - \hat{\boldsymbol{\omega}}$. The error vector of quaternion is

$$\begin{bmatrix} e_{q1} \\ e_{q2} \\ e_{q3} \\ e_{q4} \end{bmatrix} = \begin{bmatrix} \hat{q}_4 & \hat{q}_3 & -\hat{q}_2 & -\hat{q}_1 \\ -\hat{q}_3 & \hat{q}_4 & \hat{q}_1 & -\hat{q}_2 \\ \hat{q}_2 & -\hat{q}_1 & \hat{q}_4 & -\hat{q}_3 \\ \hat{q}_1 & \hat{q}_2 & \hat{q}_3 & \hat{q}_4 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{15}$$

where $\boldsymbol{e}_q = \begin{bmatrix} e_{q1} & e_{q2} & e_{q3} \end{bmatrix}^T$. This feature of the controller distinguishes it from classical proportional controllers. According to above, the feedback control law eq. (9) is augmented to:

$$\boldsymbol{u} = -\boldsymbol{K}\boldsymbol{e}_q - \boldsymbol{C}\boldsymbol{e}_\omega \tag{16}$$

In addition to this adaptive parameter k_p is defined that is also dependent on the error between the actual system and the ideal reference model. The adaptive parameter k_p should show the bias between the real spacecraft system and the reference model, which is defined as:

$$\dot{k}_p = \left\| \boldsymbol{K}\boldsymbol{e}_q \right\|^2 + \left\| \boldsymbol{C}\boldsymbol{e}_\omega \right\|^2 \tag{17}$$

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^\times \boldsymbol{J}\boldsymbol{\omega} + k_p \boldsymbol{u} \tag{18}$$

Different from other engineering systems which usually have a signal error function, the quaternion spacecraft system has two error vectors $\boldsymbol{e}_q$ and $\boldsymbol{e}_\omega$. By adding the square of norm of the two error vectors can show the bias of the real system and the reference model best. To keep the coherence of the system and to reduce the tuning requirement, we choose the parameters $\boldsymbol{K}$ and $\boldsymbol{C}$ to be the same as in equation (14). The intuition behind this control is that in the presence of a fault the controller will have to work harder to track the trajectory and thus the gain increases to compensate for this.

The Adaptive Control Logic with Actuator Gain Fault

First, the spacecraft model with actuator gain fault is taken into account. The gain fault is one of major error conditions for the actuator error. When the system has n actuators and the i st actuator is in gain failure mode, it can be described as

$$u_{iout}(t) = k_i u_{iin}(t) \tag{19}$$

where k_i is the scale factor of the gain variation and $0 < k_i < 1$. $k_i = 0$ cause the actuator in the stuck fault mode and $k_i = 1$ means the actuator is healthy.

For the nano-spacecraft, we assume that the vehicle is endowed with only three actuators and each actuator experiences gain fault mode (partial power loss) but is still active. The results are extended to the case in which there exists actuation limit on each actuator. The attitude dynamics of the spacecraft are governed by

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^\times \boldsymbol{J}\boldsymbol{\omega} + \Gamma(\cdot) k_p \boldsymbol{u} \tag{20}$$

where $\Gamma(\cdot) \in R^{3\times3}$ is the actuation effectiveness matrix of the form

$$\Gamma(\cdot) = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix} \tag{21}$$

with $0 \le k_i \le 1$ being the scale factor of the gain variation for the i th actuator. When the three actuators encounter partial power loss (gain fault mode), the actuation effectiveness matrix $\Gamma(\cdot)$ becomes uncertain or even time varying but remains positive definite.

The Adaptive Control Logic with Actuator Deviation Fault

The deviation fault is another major error condition for the actuator error. When the i th actuator is in deviation fault, it can be described as

$$u_{iout}(t) = u_{iin}(t) + a_i \tag{22}$$

where a_i is a constant. $a_i = 0$ means that the actuator works normally.

When the three actuators of spacecraft get a constant torque above or below the required torque, the attitude dynamics is shown as

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^{\times}\boldsymbol{J}\boldsymbol{\omega} + k_p\boldsymbol{u} + \boldsymbol{f}_n \tag{23}$$

where $\boldsymbol{f}_n = \begin{bmatrix} a_1 & a_2 & a_3 \end{bmatrix}^T$ is the actuation deviation matrix. a_i is the actuator deviation fault indicator for the i th thruster. Since we take a_i as a constant, the actuation deviation matrix $\boldsymbol{f}_n$ is a constant matrix.

The Adaptive Fault-Tolerant Control Logic with Control Torque Limits

Under actuator errors, the attitude dynamics of spacecraft system can be summed up

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^{\times}\boldsymbol{J}\boldsymbol{\omega} + \Gamma k_p\boldsymbol{u} + \boldsymbol{f}_n \tag{24}$$

Since nano-spacecraft always gets small actuators, the control torque which could apply is limited. [17,18,19] Take $|u_i| \le u_{\max}^i \ (i = 1,2,3)$ denote the control force of i th actuator and $u_{\max}^i > 0$. Under such a severe situation, the spacecraft system should admit a feasible attitude tracking control solution. Lead a judge parameter s as

$$s = k\left\|\boldsymbol{e}_q\right\| + c\left\|\boldsymbol{e}_{\omega}\right\| \tag{25}$$

Then the control scheme ensuring attitude tracking of nano-spacecraft under the conditions as mentioned is given by

$$\boldsymbol{u} = \begin{cases} \dfrac{u_{\max}}{sJ_{\max}}\left(-\boldsymbol{K}\boldsymbol{e}_q - \boldsymbol{C}\boldsymbol{e}_{\omega}\right) & s \ge u_{\max}/J_{\max} \\ -\boldsymbol{K}\boldsymbol{e}_q - \boldsymbol{C}\boldsymbol{e}_{\omega} & s \le u_{\max}/J_{\max} \end{cases} \tag{26}$$

where $J_{\max} = \max\{J_{11}, J_{22}, J_{33}\}$ and $u_{\max} = \min\{u_{\max}^1, u_{\max}^2, u_{\max}^3\}$.

SIMULATION STUDY

To verify the effectiveness of the proposed control scheme, simulations on UKube-1 under various conditions are conducted. This simulation is carried out under the condition that the moment inertia matrix is

$$\boldsymbol{J} = \begin{bmatrix} 0.0109 & 0 & 0 \\ 0 & 0.05 & 0 \\ 0 & 0 & 0.05 \end{bmatrix}$$

The spacecraft is to perform the maneuver that changes its attitude from the initial attitude $\boldsymbol{q}(0) = (-0.1, 0.15, -0.2)$ and $q_4(0) = \sqrt{1 - \boldsymbol{q}^T \boldsymbol{q}}$.

First, we simulate the spacecraft system under actuator gain fault and actuator deviation fault, which is compared with traditional quaternion feedback control law and adaptive fault-tolerant control law. Note that, in both controllers, one only needs to simply select the control parameters $k = 3.6$ and $c = 1.72$. Then, the simulation under actuator gain fault and actuator deviation fault of the adaptive fault-tolerant control law with limit control torque. We also choose the control parameters $k = 3.6$ and $c = 1.72$.

Actuator Gain Fault under Two Control Logic

This represents a severe case in which several actuators lose partial power with randomly varying heath levels. As shown in equation (20), the gain fault mode of the each thrusters are generated by the following function

$$k_i = 0.5 + 0.2 rand(t) + 0.3 \sin(0.5t + i\pi/3) \quad (i = 1, 2, 3) \tag{27}$$

which swings between 1 and 0.2. Simulate the same fault in both traditional quaternion feedback control method and the adaptive fault-tolerant control method. The angular velocity under both control law is shown in the figure 1. The quaternion under both control law is shown in figure 2. The control torque under both control law is shown in figure 3.

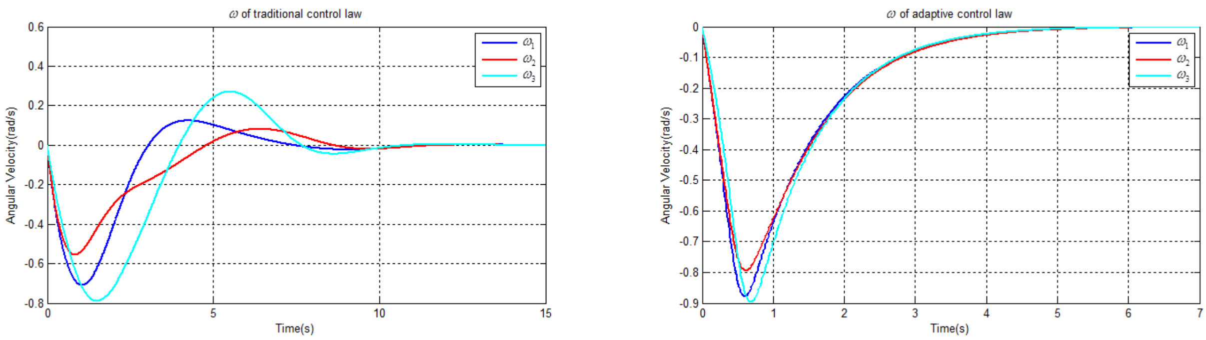

Figure 1. Angular Velocity (rad/s) During Traditional Quaternion Feedback Control Law and Adaptive Fault-Tolerant Control Law.

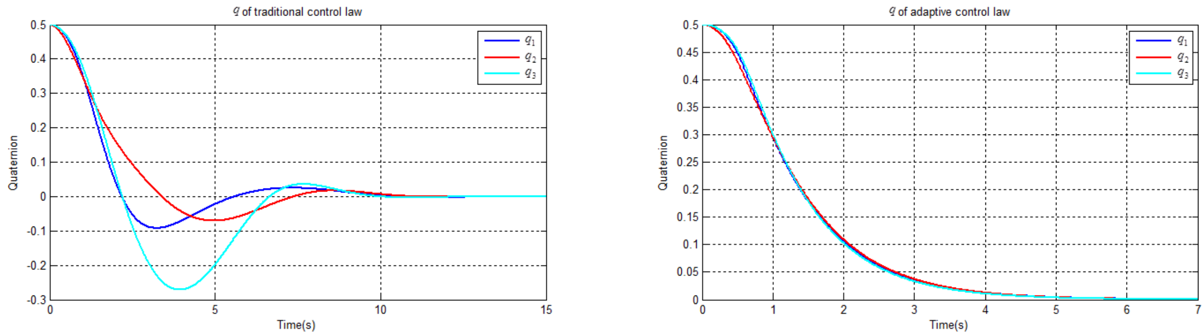

Figure 2. Quaternion During Traditional Quaternion Feedback Control Law and Adaptive Fault-Tolerant Control Law.

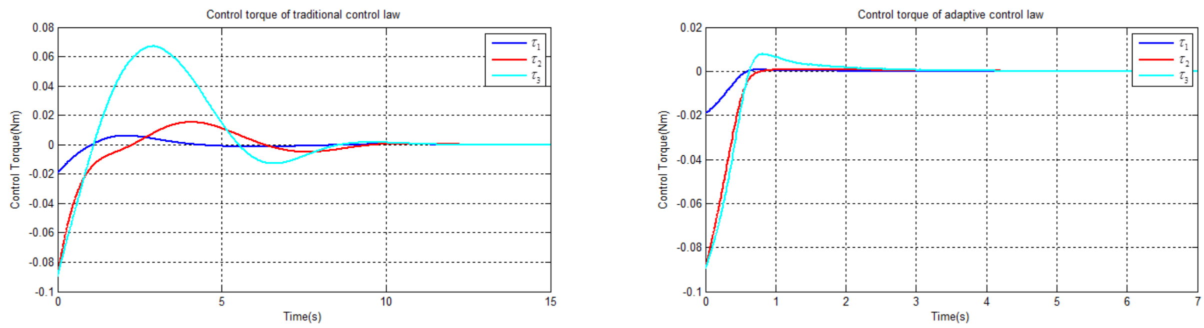

Figure 3. Control Torque During Traditional Quaternion Feedback Control Law and Adaptive Fault-Tolerant Control Law.

From the figures, we can see that the adaptive fault-tolerant control law works well under the actuator gain fault mode, not only with improved speed but also need less control torque.

Actuator Deviation Fault under Two Control Logic

This case involves actuators which is delivering a constant torque above or below the required torque. As equation (23), we set the fault as

$$a_1 = \begin{cases} 0 & t < 5s \\ 0.005 & t \geq 5s \end{cases} \qquad a_2 = 0 \qquad a_3 = 0 \tag{28}$$

The angular velocity of both control law is shown in figure 4. The quaternion under both control law is shown in figure 5. The control torque of both control law is shown in figure 6.

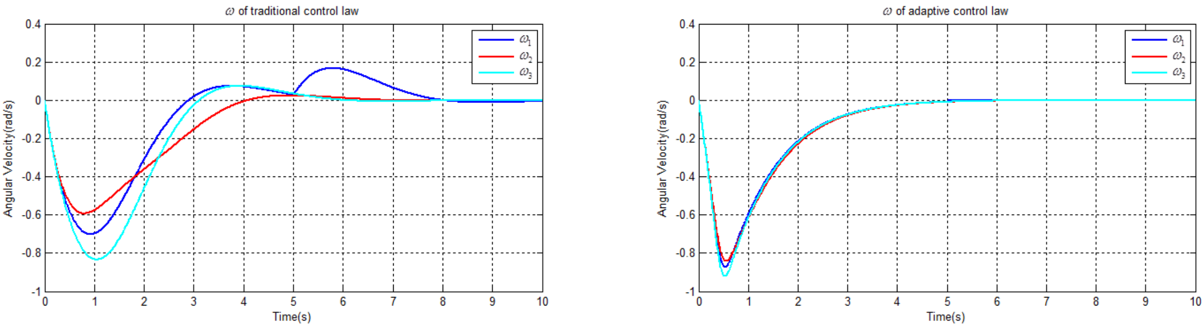

Figure 4. Angular Velocity (rad/s) During Traditional Quaternion Feedback Control Law and Adaptive Fault-Tolerant Control Law.

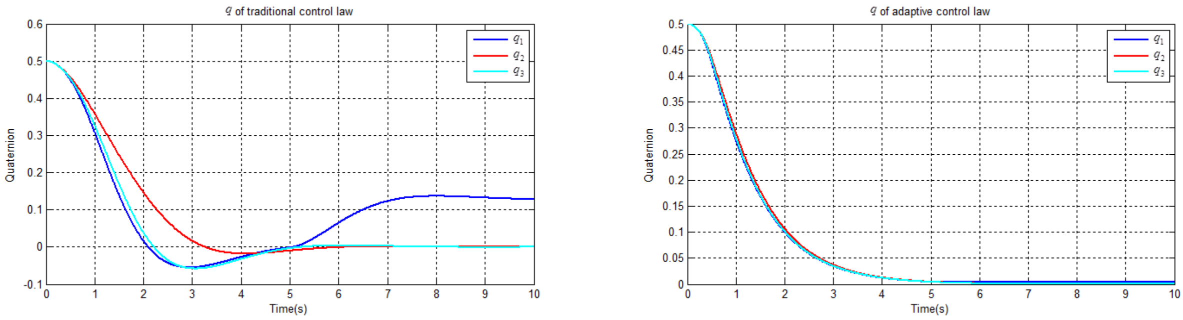

Figure 5. Quaternion During Traditional Quaternion Feedback Control Law and Adaptive Fault-Tolerant Control Law.

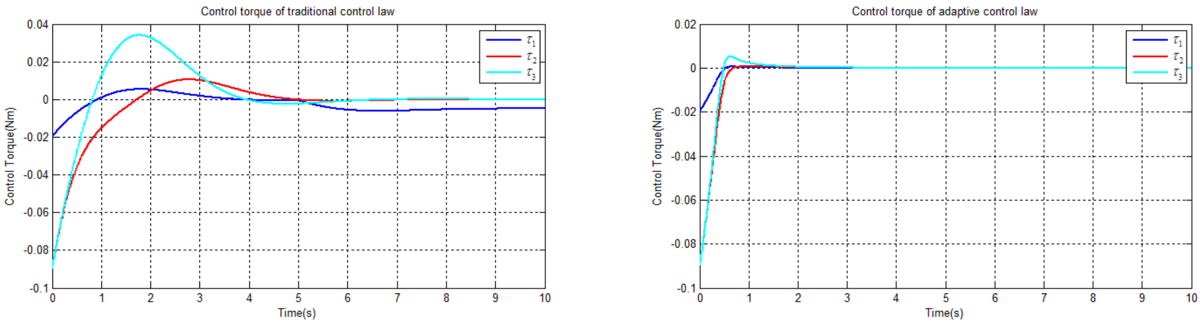

Figure 6. Control Torque During Traditional Quaternion Feedback Control Law and Adaptive Fault-Tolerant Control Law.

As shown in the figures, under actuator deviation fault mode, the traditional quaternion feedback control law couldn't track the trace well; the quaternion even deviates from a predetermined trajectory. The adaptive fault-tolerant control law still keeps steady under this situation. When actuator deviation fault happen at 5s, the system isn't change much and easily come back to the steady condition.

Actuator Gain Fault with Limit Control Torque

We assume that the spacecraft is equipped with simple reaction wheels. The wheel data is based on the Sinclair Interplanetary picosatellite reaction wheels*. The maximum wheel torque is $1\times10^{-3}\,Nm$. Simulation is combined both actuator gain fault and actuator deviation fault. The gain fault is the same as equation (27). The actuation fault is

$$
\begin{aligned}
& a_1 = \begin{cases} 0 & t < 15s \\ 0.001 & t \ge 15s \end{cases} \\
& a_2 = 0 \\
& a_3 = 0
\end{aligned}
\qquad (29)
$$

Figure 7 shows the angular velocities and the quaternions under this control logic, and figure 8 shows the control torque and adaptive parameter.

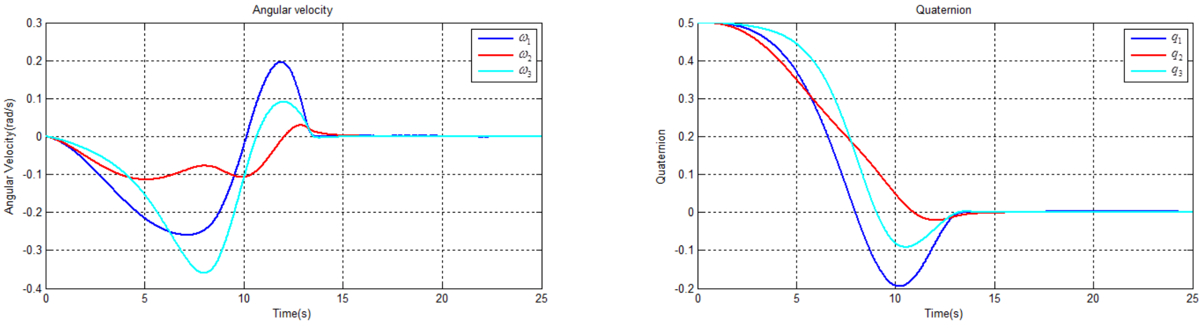

Figure 7. Angular Velocities and Quaternion

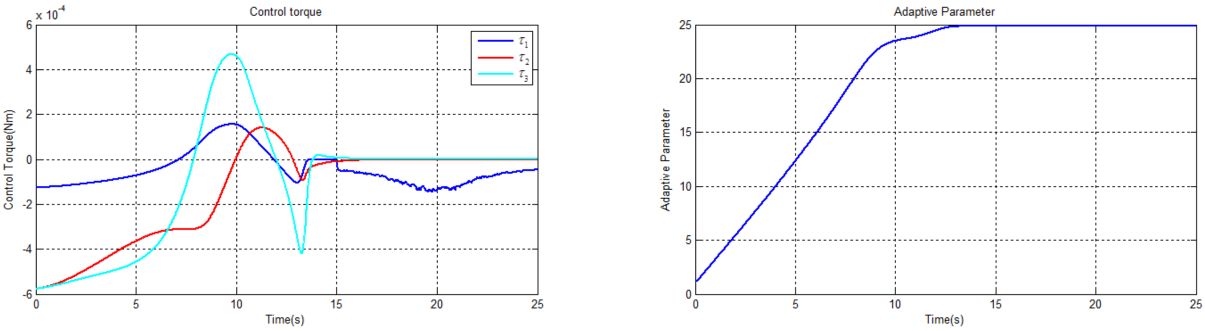

Figure 8. Control Torque and Adaptive Parameter

It is shown that fairly good control performance is achieved under such severe actuator faults combined situation with limited control torque. Since the actuator deviation fault exists on a_1, the

* http://www.sinclairinterplanetary.com/reactionwheels

control torque u_1 should be coordinated with the deviation fault instead of getting to 0. The undulating curve is set by the actuator gain fault.

The simulations on all those severe cases including the worst one all indicate that the proposed control is indeed robust, adaptive, fault-tolerant, and user/designer friendly.

CONCLUSION

An adaptive fault-tolerant control logic, which is improved from the traditional quaternion feedback control, is introduced to the nano-spacecraft. The spacecraft system is considered with an actuator gain fault and actuator deviation fault. Using the parameters of UKube-1 in the simulation example, it was shown that the ability of adaptive fault-tolerant control logic to deal with failures is significantly increased when compared to traditional quaternion feedback control logic with both an actuator gain fault and an actuator deviation fault.

ACKNOWLEDGMENTS

This work was partially supported by the Chinese Scholarship Council.

REFERENCES

[1] Bong Wie and Peter M. Barba, "Quaternion Feedback for Spacecraft Large Angle Maneuvers." *J. Guidance*. Vol. 8, No. 3, 1985, pp. 360–365.

[2] Bin Jiang, Zhifeng Gao, Peng Shi and Yufei Xu, "Adaptive Fault-Tolerant Tracking Control of Near-Space Vehicle Using Takagi-Sugeno Fuzzy Models." *IEEE Transactions on Fuzzy Systems*. Vol. 18, No. 5, 2010, pp. 1000-1007.

[3] Riccardo Marino, "Adaptive Control of Nonlinear Systems: Basic Results and Applications." *A. Rev. Control*. Vol. 21, 1997, pp. 55-66.

[4] Mak Tafazoli, "A Study of On-orbit Spacecraft Failures." *Acta Astronautica*. 64 (2009), pp. 195–205.

[5] K. M. Passino and P. J. Antsaklis, "Fault Detection and Identification in an Intelligent Restructurable Controller." *Journal of Intelligent and Robotic System*. 1 (1988), pp. 145–161.

[6] K. L. Bedingfield, R. D. Leach and M. B. Alexander, "Spacecraft System Failure and Anomalies Attributed to the Natural Space Environment." *NASA Reference Publication 1390*. 1996.

[7] Chee Pin Tang and Christopher Edwards, "Sliding Mode Observers for Robust Detection and Reconstruction of Actuator and Sensor Faults." *Int. J. Robust and Nonlinear Control*. Vol. 13, 2003, pp. 443–463.

[8] Wenchuan Cai, X. H. Liao and Y.D. Song, "Indirect Robust Adaptive Fault-Tolerant Control for Attitude Tracking of Spacecraft." *Journal of Guidance, Control, and Dynamics*. Vol. 31, No. 5, 2008, pp. 1456–1463.

[9] *Bong Wie*. Space Vehicle Dynamics and Control, Reston: American Institute of Aeronautics and Astronautics, 2nd ed., 2008.

[10] L. Psiaki, "Magnetic Torquer Attitude Control via Asymptotic Periodic Linear Quadratic Regulation." *Journal of Guidance, Control, and Dynamics*. Vol. 24, No. 2, 2001, pp. 386–394.

[11] O. Egeland and J. M. Godhavn, "Passivity-Based Adaptive Attitude Control of a Rigid Spacecraft" *IEEE Transactions on Automatic Control*. Vol. 39, No. 4, 1994, pp. 842–846.

[12] B. T. Costic, D. M. Dawson and M. S. de Queiroz et., "Quaternion-Based Adaptive Attitude Tracking Controller Without Velocity Measurements." *Journal of Guidance, Control, and Dynamics*. Vol. 24, No. 6, 2001, pp. 1214–1222.

[13] Nadjim M. Horri, Philip L. Palmer and Mark Roberts, "Energy Optimal Spacecraft Attitude Control Subject to Convergence Rate Constraints." *Control Engineering Practice*. Vol. 19, 2011, pp. 1297-1314.

[14] Craig Maclean, Daniele Pagnozzi and James D. Biggs, "Planning Natural Reporting Manoeuvres for Nano-Spacecraft." *IEEE Transactions on Electronics and Aerospace.*

[15] *Yanjun Lee and Ke Zhang*. Adaptive Control Theory and Application, Xian: Northwester Polytechnical University, 2nd ed., 2005.

[16] *Gang Tao*. Adaptive Control Design and Analysis, A Wiley-Interscience Publication, 1st ed., 2003.

[17] Jovan D. Boskovic, Sai-Ming Li and Raman K. Mehra, "Robust Tracking Control Design for Spacecraft under Control Input Saturation." *Journal of guidance, control, and Dynamics.* Vol. 27, No. 4, 2004, pp. 627-633.

[18] Zheng-Xue Li and Ben-Li Wang, "Robust Attitude Tracking Control of Spacecraft in the Presence of Disturbances." *Journal of Guidance, Control, and Dynamics.* Vol. 30, No. 4, 2007, pp. 1156-1159.

[19] Robert J. Wallsgrove and Maruthi R. Akella, "Globally Stabilizing Saturated Attitude Control in the Presence of Bounded Unknown Disturbances." *Journal of Guidance, Control, and Dynamics.* Vol. 28, No. 5, 2005, pp. 957-963.