Real-time Simulation System of Satellite Attitude Reconfigurable Control Based on VxWorks

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Abstract—Currently the most common solutions of satellite attitude control simulation systems is to establish the model of sensors, actuators and the dynamics model of satellite under normal operation. With the gradual development on areas of spacecraft based on fault detection and diagnosis(FDD) and fault-tolerant control systems(FTCS), it is necessary to design a real-time satellite attitude control simulation systems which can be used in the research on the method of reconfigurable attitude control. In this paper we focus on the need for simulation and testing of reconfigurable satellite attitude control systems based on VxWorks operating system. Not only the models of sensors, actuators on satellite under fault conditions are built on the basis of traditional simulation environment, but also the module of FDD considers the trouble of the uncertainty of parameter estimation. In addition, a human-computer interactive interface is designed to observe the dynamic parameters during the reconstruction process of the reconfiguration. Finally we verify the effectiveness of the real-time simulation system for satellite reconfigurable control study by experiment.

Keywords—Satellite Attitude Control, CAN Bus, VxWorks, Fault-tolerant Control

I. INTRODUCTION

The simulation is an important method for the research of Satellite Attitude Control system. And by this method, not all physical units are needed and it is well suited for theoretical research or validation of the feasibility in the early design stage[1][2][3]. In usual hardware-in-loop simulation for Satellite Attitude Control, the sensors and actuating mechanism as well as various models are mixed for a loop test. The real work process can be repeated with low cost[3]. Since the space environment is unknown in advance and the configuration of satellite system is large and complex, it is very prone to failure even with small faults. With the development of fault-tolerant control of spacecraft, for the research on the satellite attitude reconfigurable control technology, the requirement of a specialized simulation platform becomes urgent. The accurate estimation of system parameters which come from fault diagnosis unit is premise for reconfigurable controller. So the uncertainty of fault diagnosis is one of the main issues for reconfigurable controller design at hand[4][5].

In this paper, based on VxWorks, a real-time Simulation platform of Satellite attitude reconfigurable control is developed. Several typical fault models are introduced to the simulation platform. In order to study the effects that come from the uncertainty of fault diagnosis on control systems, an easy configuration fault diagnosis unit, which is used to set uncertain volume, is designed[4]. In addition, a friendly interference for diagnostic estimation uncertainty is designed to this platform. In order to study the relationship between the uncertainty of fault diagnosis and the performance of reconfigurable controller, the uncertainty volume can be conveniently adjusted. Moreover, with CAN communication, a person-computer alternation interface which is used to monitor the entire process from faults occurring to the controller reconfiguration accomplishment is developed. This simulation platform is well in real-time, reconfiguration process visualization and comprehensive models[6].

II. STRUCTURE OF THE SIMULATION SYSTEM

The simulation system consists of four components: emulator, controller, human-computer interactive interface and hardware failures terminal emulation module. The emulator and controllers are equipped with an industrial computer with VxWorks operating system running real-time simulation program. The main function of emulator is to simulate the dynamics equations of satellite in orbit including dynamics and kinematics model of satellite, model of sensors, actuators and environment. The controller is used as onboard computer which runs the entire algorithms of attitude control. The human-computer interactive interface is designed to observe the dynamic parameters during the reconstruction process of the reconfigurable attitude controller and to achieve some basic functions such as fault injection and initialization. The hardware failures terminal emulation module is used to simulate the device failure of on-board computer. The structure of simulation system is shown in Figure 1.

In Figure 1, the upper part of the diagram represents the hardware failures terminal emulation module, which transmits the measurement data of attitude sensors and the control commands of the controller. The communication between the emulator and the human-computer interactive interface transmit the parameters...
of models in emulator and the commands of human through Ethernet. The communication between the controller and the human-computer interactive interface transmit the remote command and status data of controller through RS-232. Human-computer interactive interface is shown in Figure 2.

III. MODELS OF SIMULATION SYSTEM

A. Kinematics and dynamics

The kinematics model of satellite can be described as

\[
\begin{bmatrix}
\dot{q}_0 \\
\dot{q}_1 \\
\dot{q}_2 \\
\dot{q}_3
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{bx} & -\omega_{by} & -\omega_{bz} \\
\omega_{bx} & 0 & -\omega_{bz} & \omega_{by} \\
\omega_{by} & \omega_{bz} & 0 & \omega_{bx} \\
\omega_{bz} & -\omega_{by} & -\omega_{bx} & 0
\end{bmatrix}
\begin{bmatrix}
q_0 \\
q_1 \\
q_2 \\
q_3
\end{bmatrix}
\]

where \( \mathbf{q} \) means the quaternion of attitude.

According to the law of angular momentum the angular momentum equation of satellite has the form

\[
I_b \dot{\mathbf{\omega}}_b + \mathbf{\omega}_b \times I_b \mathbf{\omega}_b = \mathbf{u} + T_d
\]

where \( I_b \) is the moment of inertia matrix of satellite. \( \mathbf{\omega}_b \) is the angular velocity vector for the satellite. \( \mathbf{u} \) is the control moment acting on the satellite. \( T_d \) is the disturbance torque acting on the satellite. Expand the formula above into a matrix form

\[
\begin{bmatrix}
\dot{\alpha} \\
\dot{\alpha} \\
\dot{\alpha}
\end{bmatrix} + \begin{bmatrix}
A_0 & A_1 & A_2
\end{bmatrix} \begin{bmatrix}
\alpha \\
\dot{\alpha} \\
\dot{\alpha}
\end{bmatrix} + \begin{bmatrix}
G_0 T_d + T_d \mathbf{u}
\end{bmatrix}
\]

where

\[
A_0 = \begin{bmatrix}
4(l_2 - l_3) & 3(l_1 - l_3) & l_2 - l_1 \\
3(l_1 - l_3) & 4(l_1 - l_2) & l_3 - l_2 \\
l_1 - l_2 - l_3 & l_2 - l_1 & 4(l_1 - l_3)
\end{bmatrix}
\]

\[
A_1 = \begin{bmatrix}
l_3 & 0 & -l_1 + l_2 - l_3 \\
0 & l_3 & l_2 - l_1 \\
l_1 - l_2 - l_3 & l_2 - l_1 & 0
\end{bmatrix}
\]

\[
A_2 = I_b G_d = G_u = I_{3 \times 3}
\]

B. Reaction wheels

\[
\mathbf{u} = T_w - T_f = I_{WC} K_{T_f} - T_f
\]

where \( T_w \) is the desired output torque of the reaction wheels. \( T_f \) is the friction torque of the reaction wheels. \( I_{WC} \) is the control current of the reaction wheels. \( K_{T_f} \) is the moment coefficient of the reaction wheels.

C. Star sensor

It is a very complex task to simulate star chart and star pattern recognition. The model of star sensor can be simplified as

\[
\begin{align*}
E'_x &= E_x + w_x \\
E'_y &= E_y + w_y \\
E'_z &= E_z + w_z
\end{align*}
\]

where \( E'_i \) is the measurement of Euler angles by star sensor\((i = x, y, z)\). \( E_i \) is the real Euler angles of satellite. \( w_i \) is the white noise\((i = x, y, z)\).

D. Gyroscope

\[
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix} = \mathbf{A} \mathbf{\omega}
\]

(10)

\[
\omega_0 = \omega_t + b + w
\]

(11)

\( \omega_t \) is measurement angular velocity vector of gyroscopes. \( \mathbf{\omega} \) is real angular velocity vector of gyroscopes. \( \mathbf{A} \) is installation matrix of gyroscopes. \( b \) is zero bias of gyroscopes. \( w \) is the white noise.

IV. RECONFIGURABLE CONTROL ALGORITHM

For zero momentum system, the momentum of the satellite is zero under normal situation. To avoid the influence of friction torque at zero-crossing, we use four reaction wheels of which three are orthogonally mounted and one are cant to achieve precise attitude control. Figure 3 shows the control loop modes of the controller.
The observation equation of the system is

\[ y_k = C_k x_k + v_k \]  

where \( C_k \) is a \( 6 \times 6 \) diagonal matrix.

The estimate of control effectiveness factors can be described as

\[ \hat{\gamma}_{k+1|k} = \hat{\gamma}_k \]  
\[ P^a_{k+1|k} = P^a_{k|k} + Q_a \]  

The estimate of system state variable can be described as

\[ \tilde{x}_{k+1|k} = A_k \tilde{x}_{k|k} + B_k u_k + W_k \hat{\gamma}_{k+1|k} - V_{k+1|k} \hat{\gamma}_{k|k} \]

\[ \hat{P}_{k+1|k} = A_k \hat{P}_{k|k} A_k^T + Q_a + W_k P_{k+1|k} W_k^T - V_{k+1|k} P_{k+1|k} V_{k+1|k}^T \]

The relationship between system state variable and effectiveness factors is

\[ W_k = A_k V_{k|k} - E_k^a \]

\[ V_{k+1|k} = W_k P_{k+1|k} (P_{k+1|k}^{-1} - I) \]

\[ H_{k+1|k} = C_k V_{k+1|k} \]

\[ H_{k+1|k+1} = C_k V_{k+1|k} \]

\[ V_{k+1|k+1} = V_{k+1|k} - \tilde{R}_{k+1|k} H_{k+1|k} \]

**B. Reconfigurable controller based on LQR**

LQR reconfigurable controller will be injected when a fault occurs and the effectiveness factors can be evaluated abnormal. The LQR controller will not participate in controlling while there is no fault in reaction wheels. Figure 4 shows the simulation diagram of satellite attitude control system with reconfiguration control of effectiveness factor. Detailed certification and description can be found in reference [9].

The reconfigurable controller can be designed as

\[ u_k = -K_k^e \hat{\gamma}_{k|k} \]  

\[ K_k^e = (R_k + (I - \hat{\gamma}_k^e) G_k^a (I - \hat{\gamma}_k^e)^T)^{-1} (I - \hat{\gamma}_k^e) G_k^a P_{k|k} (A_k - G_k^a (I - \hat{\gamma}_k) K_k) + K_{P_k}^e R_k K_k \]

**V. EXPERIMENT**

The experiment is tested in the condition of reaction wheel failure. In the case of different extent of failure, controller effectiveness factor changes. The experiment makes comparison of the Euler angles under the condition when the reaction wheels are in normal operation and in failure. Figure 5 shows the attitude in process of the control loop modes shown in Figure 2. Figure 6 shows the steady-state error of Euler angels. The steady-state error of Euler angels are limited less than 0.1 degree. The stability of Euler angles in control is better than 0.01 degree per second.
CONCLUSION

In this paper we focus on the need for simulation and testing of reconfigurable satellite attitude control systems based on VxWorks operating system. Several typical fault models are introduced to the simulation platform. Not only the models of sensors, actuators on satellite under fault conditions are built on the basis of traditional satellite simulations, but also the module of FDD considers the trouble of the uncertainty of parameter estimation in order to study the effects that come from the uncertainty of fault diagnosis on control systems. An easy configuration fault diagnosis unit, which is used to set uncertain volume, is designed. In addition, a human-computer interactive interface is designed to observe the dynamic parameters during the reconstruction process of the reconfiguration. Finally we verify the effectiveness of the real-time simulation system for satellite reconfigurable control study by experiment.

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