Spacecraft Attitude Fault Detection and Recovery Using Non-Linear Observer and Reconfigurable Controller

Daren Lee and Krishna Dev Kumar

***Abstract*—This paper addresses fault tolerant attitude control through the development of a fault observer and re-configurable control law. Using attitude sensor measurements for angular position and velocity, an estimate of the true torque on all three axes is accomplished using a pair of super twisting sliding mode observers. Modifications on the `broken' super twisting observer is applied in order to accommodate additional sensor feedback inputs. Using this method, reconstruction of torque faults can be accomplished and fault information is then sent to a re-configurable controller which switches to an appropriate control law to recover and mitigate the effects of the actuator fault. Simulation results are presented to show fault reconstruction and recovery with attitude stabilization in the presence of orbital disturbances - some which are partially unknown to both controller and observer.**

***Index Terms*—Spacecraft attitude detection and recovery, non-linear observer, reconfigurable controller.**

I. Introduction

Autonomous capabilities for spacecraft systems have become a source of great interest in recent years to support the requirements of future space mission needs. One application of spacecraft autonomy would include the mitigation or adaptation to attitude and orbit control system (AOCS) failures. In order to develop a fault tolerant AOCS, analytical redundancy can provide a non-hardware based implementation and relies on a method of mitigating or recovering from system errors and faults rather than having on-board redundant hardware. The paper is organized as follows: Section II presents the nonlinear spacecraft model, fault observer design, and reconfigurable controller design. Section III provides details on fault recovery. Finally, Section IV details the results of this fault detection, isolatoion and recovery (FDIR) methodology under different test scenarios.

II. Spacecraft Model, Fault Observer Design and Reconfigurable Controller Design

The attitude equations of motion of a rigid spacecraft orbiting the Earth can be expressed as

$$\ddot{q} = N(q)[F(q,\dot{q}) + U + T] \qquad (1)$$

where $q = [\alpha, \phi, \gamma]^T$, represents the attitude vector denoted by Euler angles (α =pitch, ϕ =roll, γ =yaw). $F(q,\dot{q})$ denotes the terms due to coriolis and centripetal accelerations. $U = [U_\alpha, U_\phi, U_\gamma]^T$ denotes control torques and T represents external disturbance torques due to Earth's gravity, solar radiation pressure and aerodynamic drag.

Fig. 1 depicts the formulation of the proposed fault detection system. The proposed autonomous fault detection and recovery algorithm here first uses the sliding mode observer to detect and accurately reconstruct torque faults. When torque mismatches occur between the commanded and estimated value, a controller reconfiguration takes place, switching to an appropriate control mode to match the fault scenario. It is assumed that no fault occurs on the pitch axis, which is completely de-coupled from the roll and yaw dynamics. The entire fault detection and recovery scheme is shown in Fig. 2.

III. Results and Discussion

For all cases, the following faults in Table 1 were applied to the spacecraft using the orbital parameters specified in Table 2. The proposed Sliding Mode Observer fault estimator is examined under the conditions of external disturbances in the form of solar radiation pressure (SRP) and aerodynamic drag. Using the same sensor noise and fault characteristics as in Case A, the orbital scenario remained mostly the same with the exception of the plant model containing the non-linear attitude dynamics. The disturbances due to solar radiation pressure can be expressed as (in Nm) [2],

$$T_s = \begin{bmatrix} T_{s\alpha} \\ T_{s\phi} \\ T_{s\gamma} \end{bmatrix} = S_f \begin{bmatrix} (1\times10^{-4})\cos(\dot{\theta}t) \\ (2\times10^{-5})[1-2\sin(\dot{\theta}t)] \\ (5\times10^{-5})\cos(\dot{\theta}t) \end{bmatrix} \qquad (2)$$

The external torque due to aerodynamic drag [3] can be modeled as bias plus cyclic terms in the body-fixed control axes (in Nm),

$$T_a = \begin{bmatrix} T_{a\alpha} \\ T_{a\phi} \\ T_{a\gamma} \end{bmatrix} = 1.36 A_f \begin{bmatrix} -[4+2\sin(\dot{\theta}t)+0.5\sin(2\dot{\theta}t)] \\ 1+\sin(\dot{\theta}t)+0.5\sin(2\dot{\theta}t) \\ -[1+\sin(\dot{\theta}t)+0.5\sin(2\dot{\theta}t)] \end{bmatrix} \qquad (3)$$

where S_f and A_f are positive scaling factors. The disturbance torque simulated is of the form $T_d = T_a + T_s$.

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Daren Lee and Krishna Dev Kumar are with the Department of Aerospace Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada M5B 2K3 (e-mail: kdkumar@ryerson.ca).

By choosing scaling factors as $S_f = 0.01$ and $A_f = 2\times10^{-6}$ disturbance dynamics represented by (Eqs. 3 and 2) can emulate the disturbance process due to solar radiation pressure, aerodynamic drag, and magnetic forces. For a spacecraft in LEO (500 km) this is approximately $\| T_d \| \leq 2\times10^{-5}$ Nm [4].

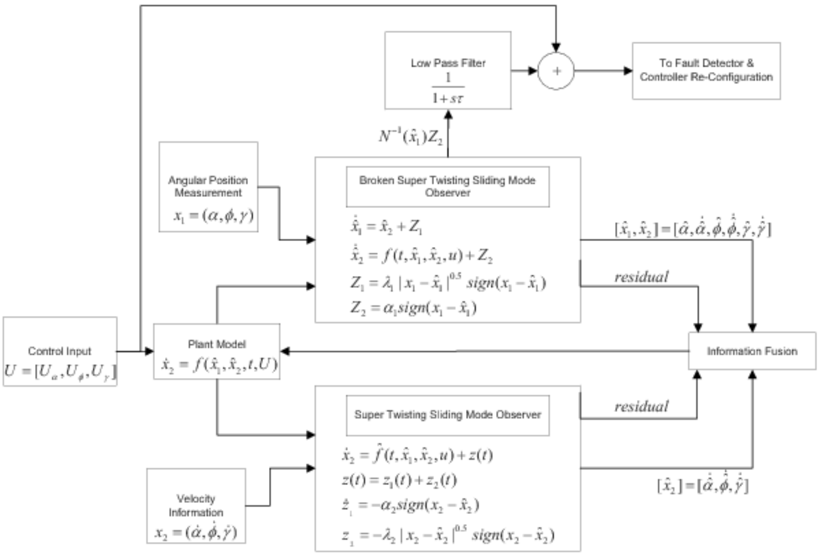

Fig. 1. Proposed sliding mode observer system for FDI.

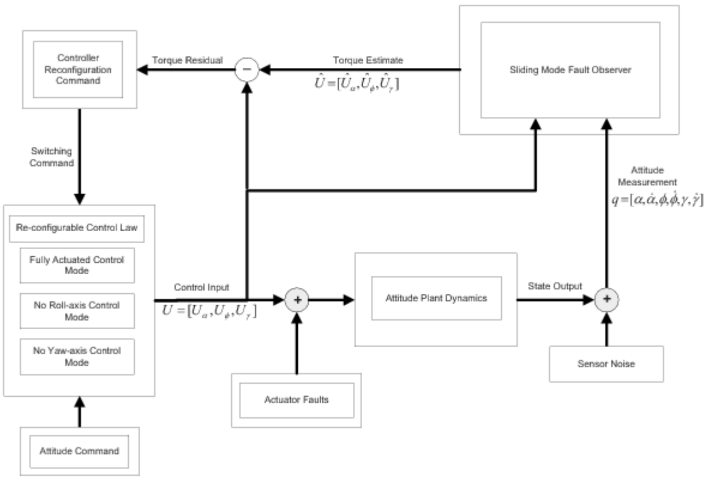

Fig. 2. Reconfigurable controller.

Fig. 3, Fig. 4 and Fig. 5 demonstrate the sliding mode fault observer tracking the faults and reconfiguring the controller to maintain stable attitude states during roll and yaw-axis faults. Fig. 5 shows the control logic mode for the roll and yaw axes, which closely coincides with the faults applied at the specified durations for the simulation.

TABLE I: TORQUE FAULTS APPLIED TO SPACECRAFT.

Axis	**Case 1:** t > 3000 and t < 8000	**Case 2:** t > 95000 and t < 16500
U_α	U_α	U_α
U_ϕ	0	U_ϕ
U_γ	U_γ	0

TABLE II: UNDERACTUATED ATTITUDE - SIMULATION PARAMETERS.

Parameters	**Values**
Orbit	
r_p (km)	6878
μ_e (km^{3}s^{-2})	398600
e	0
Spacecraft MOI	
I_{xx} (kgm^2)	10
I_{yy} (kgm^2)	17
I_{zz} (kgm^2)	15
Initial Conditions	
$[\alpha_0, \phi_0, \gamma_0]$	$[80^\circ, -40^\circ, 40^\circ]$
$[\alpha_0', \phi_0', \gamma_0']$	[0.001,0.001,0.001]

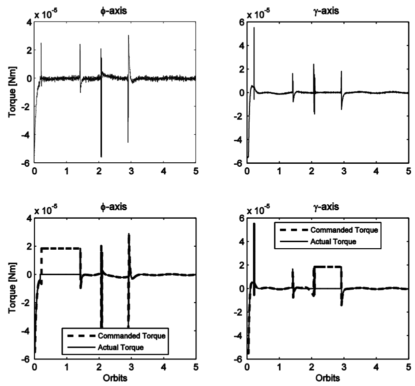

Fig. 3. External disturbance - torque estimation. Top left/right: torque estimation. Bottom left/right: commanded and actual torque.

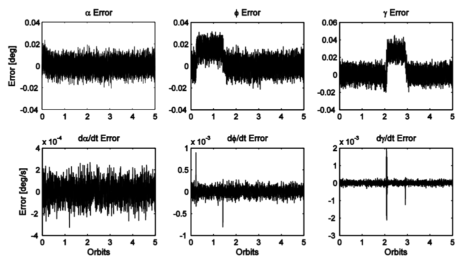

Fig. 4. External disturbance case - observer error for attitude fault recovery.

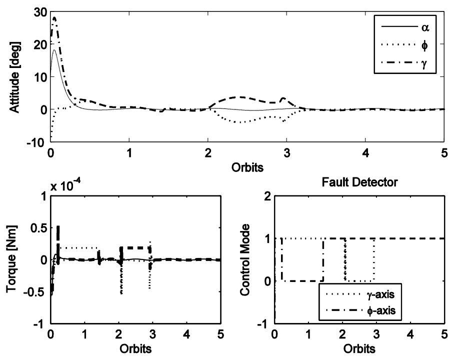

Fig. 5. External disturbance case - top: attitude states. bottom left: control effort; bottom right: fault detection logic..

IV. Conclusions

Successful detection and recovery of spacecraft attitude actuator faults have been demonstrated in different scenarios, including in the presence of external disturbances, uncertainties and sensor measurement noise. Additionally, the observer has shown acceptable resilience to noise, being capable of resolving a state estimate of the system an order of magnitude less than the noise applied to the system. With accurate fault reconstruction demonstrated, it is shown that it is possible to use this information to recover from a no-roll/no-yaw underactuated scenario. By comparing the estimated torque with the applied controller torque, it can be determined which axis is at fault and react with a controller re-configuration to mitigate effects of the fault. Using a nonlinear variable structure technique, a sliding mode controller is developed for the aforementioned fault cases and is shown to provide 3-axis stabilization of a spacecraft in LEO experiencing no roll or yaw control at different times during its mission. The development of this FDIR technique addresses many concerns and requirements relevant to future space mission needs, such as autonomous operation capable of adapting to system errors or faults. This method relies on analytical redundancy, requiring no additional hardware to accommodate its fault tolerant capabilities, thus being applicable to space missions involving small spacecraft.

References

[1] Godard and K. Kumar, "Robust attitude stabilization of spacecraft subject to actuator failures," *Acta Astronautica*, 2011, vol. 68, no. 7-8, 2011, pp. 1242–1259.

[2] M. Kaplan, "Modern Spacecraft Dynamics and Control," *John Wiley and Sons*, New York, NY, 1976.

[3] B. Wie, *Space Vehicle Dynamics and Control*, AIAA Inc., Reston, VA, 1998.

[4] J. Wertz and W. Larson, *Space Mission Analysis and Design*, Microcosm and Kluwer, New York, NY, 3rd ed., 1999.