Direct Fault Tolerant RLV Attitude Control – A Singular Perturbation Approach

J. J. Zhu1, D. A. Lawrence, J. Fisher, Y. B. Shtessel, A. S. Hodel, and P. Lu

An Extended Abstract Submitted to the 2002 AIAA GNC Conference
January 2002

ABSTRACT

In this paper, we present a direct fault tolerant control (DFTC) technique, where by "direct" we mean that no explicit fault identification is used. The technique will be presented for the attitude controller (autopilot) for a reusable launch vehicle (RLV), although in principle it can be applied to many other applications. Any partial or complete failure of control actuators and effectors will be inferred from saturation of one or more commanded control signals generated by the controller. The saturation causes a reduction in the effective gain, or bandwidth of the feedback loop, which can be modeled as an increase in singular perturbation in the loop. In order to maintain stability, the bandwidth of the nominal (reduced-order) system will be reduced proportionally according to the singular perturbation theory. The presented DFTC technique automatically handles momentary saturations and integrator windup caused by excessive disturbances, guidance command or dispersions under normal vehicle conditions. For multi-input, multi-output (MIMO) systems with redundant control effectors, such as the RLV attitude control system, an algorithm is presented for determining the direction of bandwidth cutback using the method of minimum-time optimal control with constrained control in order to maintain the best performance that is possible with the reduced control authority. Other bandwidth cutback logic, such as one that preserves the commanded direction of the bandwidth or favors a preferred direction when the commanded direction cannot be achieved, is also discussed. In this extended abstract, a simplistic example is proved to demonstrate the idea. In the final paper, test results on the high fidelity 6-DOF X-33 model with severe dispersions will be presented.

1. Introduction

Typical fault tolerant control techniques include integration supervisor, failure detection and identification, followed by control reconfiguration. The paper [Bab96] discusses an approach developed for integrating the systems such that the fault tolerance requirements were met for all stages of assembly. Some of the key integration issues are examined and the role of analysis tools is described [Bab96]. A flexible flight control architecture that meets requirements for low-cost and high reliability of the launch vehicle is presented in the paper [FT90]. It provides design

1 Corresponding author, zhuj@ohio.edu

workarounds to optimize the system to meet its mission requirements. In the paper [CR94] the design of a fuzzy logic supervisor for a reconfigurable flight control law is described. The objective of the supervisor is to maintain the original performance of the aircraft after effector failure by adjusting the gains of the existing control law. The paper [Bar92] demonstrates an innovative fault-tolerant approach that captures the knowledge of functional decomposition, failure modes and effects analysis and configuration management in a dynamic prototyping process. In the paper [WSK+00] an open software architecture, called the Open Control Platform (OCP), for integrating control technologies and resources is described. The specific driving application is supporting autonomous control of vertical take-off and landing (VTOL) uninhabited autonomous vehicles (UAVs).

Extensive research has been done in fault detection and identification. In the paper [BLM00] a stable scheme for bias estimation in the case of attitude tracking is presented. The scheme is based on the design of nonlinear observers for unknown bias identification and state estimation. The properties of the proposed scheme are evaluated through simulations using a generic spacecraft model [BLM00].

The paper [Rau94] gives an overview of fault diagnosis and control reconfiguration for complex systems such as those required in the aerospace industry. The paper [BGM99] describes a systematic computer-aided design procedure for Failure Detection and Identification (FDI) and Adaptive Reconfigurable Control (ARC) for aerospace applications.

In the paper [JL00] a geometric approach is developed for the model matching problem specific to the reconfigurable control situation where failed control surfaces have to be emulated by differential thrust. In the paper [WGW99] Quantitative Feedback Theory (QFT) was applied successfully to enhance the robust stability and tracking performance of the pitch flight control system for a remote pilotless vehicle (RPV), within its full flight envelope.

Autonomous unmanned systems require provision for fault detection and recovery. Multiply-redundant schemes typically used in aerospace applications are prohibitively expensive and inappropriate solution for unmanned systems where low cost and small size are critical. Aurora Flight Sciences is developing alternative low-cost, fault-tolerant control (FTC) capabilities, incorporating failure detection and isolation, and control reconfiguration algorithms into aircraft flight control systems. In the paper [VM96] a 'monitoring observer', or failure detection filter, predicts the future aircraft state based on prior control inputs and measurements, and interprets discrepancies between the output of the two systems. The fault-tolerant control (FTC) detects and isolates the onset of a sensor or actuator failure in real-time, and automatically reconfigures the control laws to maintain full control authority [VM96].

A technique for the design of flight control systems that can accommodate a set of actuator failures is presented in the paper [HSC00]. As employed herein, an actuator failure is defined as a change in the parametric model of the actuator that can adversely affect actuator performance. The technique is based on the formulation of a fixed feedback topology that ensures at least stability in the presence of the failures in the set. Application to a single-input/single-output design using a simplified model of the longitudinal dynamics of the NASA High-Angle-of-Attack Research Vehicle is discussed [HSC00]. The principles underlying the fault-tolerant controller are also presented in the paper [HC97].

The paper [BDR95] describes how fault tolerance has been addressed in the design of the Attitude and Articulation Control Subsystem for the Saturn-bound Cassini spacecraft. The paper [MAG+89] describes a fault-tolerant system for attitude and orbit control of Insat II spacecraft. In the paper [PTD92] the Redundant Inertial Flight Control Assembly (RIFCA) is presented, which is a system that offers a practical implementation of fault tolerant avionics through redundancy.

A guidance system with reconfiguration capabilities applicable to reusable launch vehicles is proposed in [SWM+01]. The goal is to detect effector failure using on-line parameter identification, adapt the inner-loop control system via a prescribed gain schedule to recover some maneuvering capability, and employ on-line trajectory generation if necessary. This approach is presented via a case study involving the X-34 RLV. The on-line trajectory generation scheme builds upon the authors' prior work on off-line trajectory design. A new supervisory scheme for robust on-line failure detection and isolation and adaptive reconfigurable control is presented in [BLM01]. The approach is demonstrated through simulated carrier landings of an F/A-18C/D aircraft in the presence of battle damage and critical subsystem failures. To circumvent difficulties stemming from an incorrect assumption of relatively fast effector dynamics, a technique is presented in [VD01] for compensating individual effector dynamics while respecting actuator constraints. In [BC01], a method for pre-designing controllers for a switching control scheme for systems undergoing actuator failure is described. The approach accommodates actuators frozen at non-zero positions using a steady-state disturbance rejection technique.

Control reconfiguration features must be included into the guidance and control system design for the 2nd generation RLV to accommodate actuator failures. It is noted that all the fault tolerant control techniques reviewed rely on some fault identification procedure, which in general require large computational resource while providing limited fault recognition capabilities. The separate control reconfiguration procedures will introduce additional delay in responding to faults, which may reduce survivability.

In this paper, we propose a direct fault tolerant control (DFTC) algorithm that does not depend on explicit fault identification. Control effector failures will be inferred from degradation of control authority as indicated by control command saturation, and controller gain will be adjusted based on the singular perturbation principle to ensure stability in the presence of failure. This approach requires minimal computational resources while promising fast response to undetected failures as well as large dispersions. The presented DFTC technique automatically handles momentary saturations and integrator windup caused by excessive disturbances, guidance command or dispersions under normal vehicle conditions. For multi-input, multi-output (MIMO) systems with redundant control effectors, such as the RLV attitude control system, an algorithm is presented for determining the direction of bandwidth cutback using the method of minimum-time optimal control with constrained control in order to maintain the best performance that is possible with the reduced control authority. Other bandwidth cutback logic, such as one that preserves the commanded direction of the bandwidth or favors a preferred direction when the commanded direction cannot be achieved, is also discussed. In this extended abstract, a simplistic example is proved to demonstrate the idea. In the final paper, test results on the high fidelity 6-DOF X-33 model with severe dispersions will be presented.

2. Singular Perturbation Approach to DFTC

From the vehicle health and integrity point of view, failures of control actuators or effectors, hereafter indiscriminately called effectors, are different from saturation of the fully functional effectors in the sense that an actuator failure results in *permanent* loss of use of the failed effector, whereas actuator saturation typically results in *temporary* loss of use of the actuator. However, both type of events have the same effects on the vehicle, that is the reduction in control authority.

From this point of view, a stuck aero-surface is equivalent to a constant wind gust with control saturation, and a degraded aero-surface or RCS effector is equivalent to a fully functional effector subject to a disturbance torque. The controller cannot tell nor does it care whether control command saturation is due to wind gust or a stuck effector, because it only computes the required torque, based on the vehicle's mass property and the bandwidth (in a loose sense for nonlinear systems) of the feedback loop, to eliminate the tracking error. A truly adaptive controller should be able to do this even if the vehicle has lost significant control authority due to control effector failure. It is up to the combination of the control allocation and the control effectors to realize the required torque.

The loss of control authority will eventually result in an increase in the tracking error, which will in turn cause the proportional and integral (PI) controller to produce excessive control command, such as the torque command to the control allocation unit or the body rate command to the body rate inner loop. Thus, controller adaptation can be triggered when the control command exceeds a threshold that can be easily determined in real time. This is the philosophy of the direct fault tolerant control, as no explicit fault identification is used for the adaptation. Of course, any knowledge of the specific failure will be valuable for accurately determining the threshold of available control authority that triggers the adaptation, for the reconfiguration of the control allocation law, and for abort decisions.

Neglecting the flexible modes, the closed-loop vehicle dynamic behavior is governed by the rigid body equations of motion under applied forces and moments that are determined by the controller solely by the vehicle's mass properties and the (nonlinear) loop bandwidth in the sense of signal attenuation and time lag in propagating through the loop. Thus, as long as the vehicle mass property is not altered significantly in an unknown fashion due to the failures, which is highly unlikely, the only change to the attitude control algorithm is to account for the bandwidth change due to momentary or permanent control command saturation. This can be formulated as a singular perturbation problem as follows.

Consider the singularly perturbed, closed-loop nonlinear tracking error dynamics modeled by

$$\begin{aligned}
\dot{x} &= f(t, x, v) \\
\varepsilon \dot{z} &= \mathrm{sat}(A(t)z + B(t)u) \\
v &= C(t)z \\
\dot{w} &= F(t)w + G(t)x \\
u &= M(t)w + N(t)x
\end{aligned}$$

where $\mathrm{sat}(\cdot)$ is the saturation function, x is the tracking error state variable of the "nominal" system, z is the state variable of the singular perturbation which may be an inner loop, or the dynamics of the control actuators or effectors, and w is the state variable of a linear dynamic feedback controller for the nominal system. For instance, $F(t)=0$, $G(t)=I$, $M(t)=K_I(t)$, and $N(t)=K_P(t)$ represent a PI controller where w is the error integral, and the time varying integral gain $K_I(t)$ is applied at the output of the integrator. Note that for time varying gains, this is different from the case where the integral gain $K_I(t)$ is applied at the input of the integrator, for which $M(t)=I$ and $G(t)=K_I(t)$. A block diagram of this system is given in Figure 1.

We assume that by design the null equilibriums $x=0$ and $y=0$ for the boundary layer equation $\varepsilon \dot{y} = \mathrm{sat}(A(t)y)$ are exponentially stable. The parameter $\varepsilon > 0$ is a sufficiently small constant whereby $1/\varepsilon$ represents the separation of time scale of the fast dynamics $y(t)$ and the slow dynamics $x(t)$. By a well-known result in the singular perturbation theory [Kha96], there exists an $\varepsilon^* > 0$ such that $\varepsilon < \varepsilon^*$ ensures the exponential stability of the overall system.

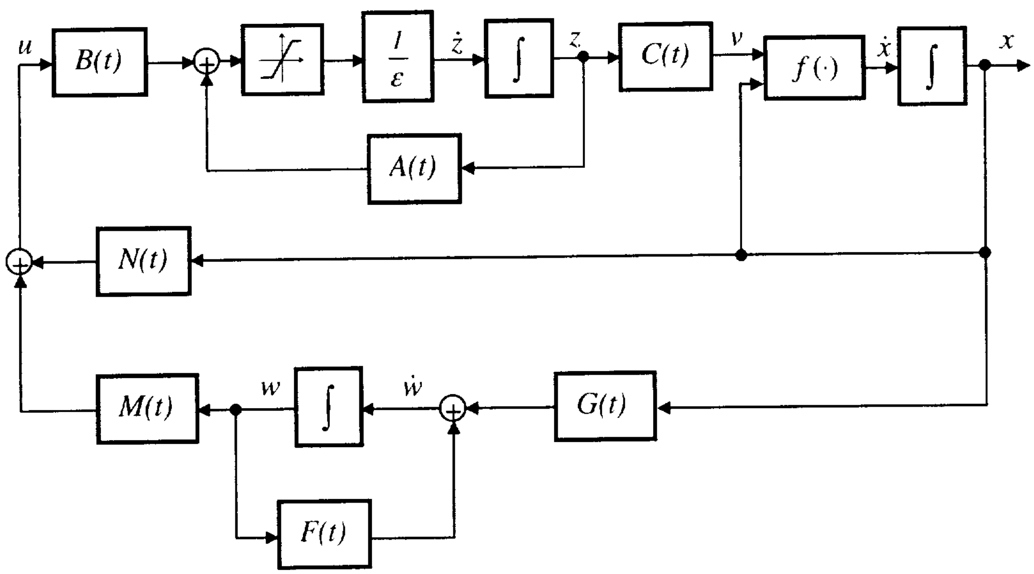

Figure 1. Singularly Perturbed System Model

The parameter ε can be approximated by the ratio between the outer loop (input, state and time dependent) bandwidth $\omega_{n,\text{outer}}$ and the inner loop bandwidth $\omega_{n,\text{inner}}$ as

$$\varepsilon = \frac{\omega_{n,\text{outer}}}{\omega_{n,\text{inner}}}$$

The saturation function can be approximated by a linear function with a variable gain $K_{\text{eff}}(a)$ dependent on some indicator a for the "depth of saturation" as follows

$$\text{sat}(x) \approx K_{eff}(a)x$$

where $K_{\text{eff}} \to 0$ as the saturation deepens. With this approximation, the singular perturbation equation for z can be approximated by

$$\varepsilon_{\text{eff}}(a)\dot{z} = A(t)z + B(t)u$$

where the effective time scale separation parameter $\varepsilon_{\text{eff}}(a)$ is given by

$$\varepsilon_{\text{eff}}(a) = \frac{\varepsilon}{K_{\text{eff}}(a)}.$$

Thus, as saturation deepens, the $\varepsilon_{\text{eff}}(a)$ will continue to grow until the required time scale separation for the overall stability is violated. On the other hand, if the outer loop bandwidth can be reduced in real time by a factor of $K_{\text{eff}}(a)$, the overall stability will be maintained, albeit that the tracking performance will be sacrificed. Note that this degraded tracking performance amounts to a reduction in control authority for the next outer loop, such as the guidance loop. Thus, the same principle can be used to scale back the guidance loop bandwidth until it is determined that the crippled vehicle can no longer accomplish the original mission goal or maintain safe flight. At that time, an abort decision can be made.

In order to adjust the bandwidth, a meaningful metric of the "depth of saturation" needs to be defined. An instantaneous metric $a(t)$ can be defined as the ratio of the commanded control versus the available control, such as the commanded torque and the available torque as determined by the control allocation unit, or the commanded aero-surface deflection angle versus the (nominal) limit of the aero-surface deflection angle. However, such instantaneous metric does not take into account of the "duty cycle" of the saturation over a period. A classical approach to this problem is the describing function for periodic saturations. For aperiodic saturations, we propose to use the integration of a nonlinear function $\kappa(a(t))$ over a specified moving time interval

$$a_{\text{eff}}(t) = \frac{\int_{t-T}^{t} \kappa(a(\tau))d\tau}{T}$$

where $\kappa(\cdot)$ is an appropriate Class-K function such that $\kappa(0)=0$, $\kappa(1)=1$, $\kappa(a)\le a\ \forall a<1$, and $\kappa(a)>a\ \forall a>1$. A convenient choice for such a $\kappa(\cdot)$ is $\kappa(a)=a^r$ for some $r>1$.

3. Time-Varying Bandwidth DFTC

The proposed fault tolerant attitude controller takes advantage of the time-varying PD-eigenvalue assignment stabilization technique used in the trajectory linearization controller (TLC) [ZBH00] and [ZFH+01], and the recently developed time varying sliding mode controller (TV-SMC) [SZD02]. The time varying bandwidth synthesis formula is given in [ZM98] and [Zhu98]. In this section, design case studies of a TV-SMC and/or a TLC attitude controller for an RLV will be presented to demonstrate the DFTC technique.

4. An Optimal Policy for MIMO DFTC Bandwidth Adjustment

Although performance degradation is inevitable when control commands saturate, for MIMO systems with redundant control effectors more control authority can be allocated to the more demanding output channels to achieve the best performance possible under the degraded control authority. This can be accomplished by developing an optimal policy for determining the direction of the available control authority, and consequently determine the direction of the depth of saturation a and the effective gain $K_{\text{eff}}(a)$ for the DFTC bandwidth adjustment. For flight control systems, this can be formulated as a problem of minimum-time optimal control with control constraints.

Taking the control torque saturation for example, suppose at each control time instant the control allocation unit can provide the (state dependent) maximum attainable moments set S. When the commanded torque $\tau_c(t)=[L_c(t)\quad M_c(t)\quad N_c(t)]^{\mathrm{T}}$ falls outside S, the objective is to find an attainable torque $\tau_a(t)=[L_a(t)\quad M_a(t)\quad N_a(t)]^{\mathrm{T}}\in S$ that minimizes the time T that it takes to bring the current tracking error $x(t_0) = x_0$ to a desirable state $x(T) = x_T$. Then the instantaneous depth of saturation is given by

$$a(t) = \begin{bmatrix} \frac{L_c(t)}{L_a(t)} & \frac{M_c(t)}{M_a(t)} & \frac{N_c(t)}{N_a(t)} \end{bmatrix}^{\mathrm{T}}.$$

The optimal attainable torque can be found by solving the standard minimum-time optimal control problem for the nominal system, that is, minimizing the minimum-time performance index

$$J = \int_{t_0}^{t_0+T} 1\, dt$$

subject to (see Equation (1))

$$\begin{aligned} \dot{x} &= f(t, x, v) \\ v(t,x) &= -C(t)A^{-1}(t)B(t)u(t,x) = \tau(t,x) \in S \\ x(t_0) &= x_0, \quad x(T) = x_T(t_0) \end{aligned}$$

where the desirable final state $x_T(t_0)$ is chosen at t_0 based on the criticality of the tracking error in each channel, which will influence the direction of the allocated torque.

It is noted that the minimum time $T_{\min}$ serves as an indicator for the performance degradation. When $T_{\min}$ exceeds a certain threshold, the guidance loop will have to reduce the bandwidth as well, or abort may be necessary. It is also noted that the allocated torque is different from the applied torque that is actually generated by the control effectors. The difference between them is the torque loop tracking error to be handled by the dynamic control allocation algorithm. The coordination of the guidance, attitude control and control allocation loops and abort decisions will be made by a supervisory controller called autocommander.

5. An Illustrative Example

Consider the attitude kinematics and rotational dynamics associated with the equations of motion of a rigid body

$$\begin{aligned} \dot{\gamma}(t) &= R(\gamma(t))\omega(t) \\ \dot{h}(t) &= -\omega(t) \times h(t) + \tau(t) \\ h(t) &= J(t)\omega(t) \end{aligned}$$

in which $\gamma = [\phi \quad \theta \quad \psi]^T$ is the vector of Euler angles, $\omega = [p \quad q \quad r]^T$ is the vector of body axis angular velocities, h is the associated angular momentum, $\tau = [L \quad M \quad N]^T$ is the vector of applied torques referenced to the body frame, and J is the inertia matrix.

With the goal of explicitly characterizing the effect that torque saturation has on effective gain and deriving a heuristic gain adaptation policy, we begin with simple proportional inner and outer loop control laws given by

$$\tau_c(t) = K_{inner} J(t)\,(\omega_c(t) - \omega(t))$$
$$\omega_c(t) = K_{outer} R^{-1}(\gamma(t))\,(\gamma_c(t) - \gamma(t))$$

where K_{inner} and K_{outer} are scalar gain parameters and $\gamma_c(t)$ represents commanded Euler angles generated by the guidance law. Here, following the singular perturbation philosophy, the idea is to design a "fast" inner loop with respect the outer loop dynamics so that if $\omega(t) \approx \omega_c(t)$, the outer loop control law achieves approximate dynamic inversion with linear outer loop dynamics whose bandwidth is determined by the gain parameter K_{outer}. This assumption then requires that

$$\varepsilon = \frac{K_{outer}}{K_{inner}}$$

be sufficiently small.

The difficulty one encounters when implementing this control strategy is that it may not be possible to achieve the commanded torque demanded by the inner loop control law. To explore this issue further, we assume that corresponding to an attainable moment set S, the control allocation strategy is such that the achieved torque is in the same direction as the commanded torque. That is,

$$\tau(t) = \sigma(\tau_c(t))\,\tau_c(t)$$

where

$$\sigma(\tau_c): \begin{cases} = 1 & if\ \tau_c \in S \\ < 1 & if\ \tau_c \notin S \end{cases}$$

in such a way that the achieved torque equals the commanded torque if the latter lies within the attainable moment set and the achieved torque lies on the boundary of the attainable moment set in the direction of the commanded torque otherwise.

The inner loop with torque saturation can be analyzed using the Lyapunov function

$$V_{inner}(h) = \tfrac{1}{2}\|h\|^2 .$$

Since h is always orthogonal to the cross product term $\omega \times h$, the derivative of $V_{inner}(h)$ along inner loop trajectories is

$$\dot{V}_{inner}(h) = \sigma(\tau_c)\,K_{inner}\,h^T(h_c - h)$$

where $h_c = J(t)\,\omega_c$. The similarity between this result and that corresponding to a first-order linear system suggests that an effective measure of inner loop gain (bandwidth) is the original gain parameter K_{inner} scaled by the saturation factor $\sigma(\tau_c)$. Scaling the outer loop gain parameter K_{outer} by the same factor would maintain the required value of ε, however the modified control laws may not be well-posed since an algebraic loop is introduced. This problem can be circumvented by filtering the saturation factor which leads to the control law

$$\tau_c(t) = K_{inner} J(t)\,(\omega_c(t) - \omega(t))$$
$$\dot{\sigma}_f(t) = K_f(\sigma(\tau_c(t)) - \sigma_f(t))$$
$$\omega_c(t) = \sigma_f(t)\,K_{outer} R^{-1}(\gamma(t))\,(\gamma_c(t) - \gamma(t))$$

in which $\sigma_f(t)$ is the filtered scale factor and K_f is a filter parameter.

Nonlinear simulations were conducted using guidance command and time-varying inertia profiles representing the X-33 during ascent. Gain parameters were selected as $K_{outer} = 1$ and $K_{inner} = 5$. This value of K_{outer} yields reasonable tracking performance in the ideal case of an instantaneous inner loop without saturation, as depicted in Fig. 2. The value of K_{inner} yields a sufficiently fast inner loop without torque saturation since the resulting outer loop attitude tracking performance, depicted in Fig. 3, is nearly identical to the ideal case. Based on the corresponding commanded/achieved torque response in Fig. 4, saturation limits of 5000 *N-m* were subsequently imposed independently in each body axis channel, for which the associated attainable moment set is a three-dimensional hypercube. The effect of saturation without gain adaptation is evident from the attitude tracking response shown in Fig. 5 and the achieved torque response shown in Fig 6. The modified control law using the filtered scale factor yields the attitude tracking response shown in Fig. 7 and the achieved torque response shown in Fig. 8. Here we see that tracking performance suffers somewhat during the initial portion of the ascent in which the torques required to closely track the attitude command greatly exceed the imposed limits (recall Fig. 4) and the outer loop gain is significantly reduced based on the gain adaptation policy described above. However, once the commanded torques recede to within limits, the outer loop gain is restored to its nominal value and nominal tracking performance is recovered.

6. Summary and Conclusions

In this section, the main results of this paper will be summarized. The advantages and disadvantages of the DFTC technique will be discussed, and further research for improving the technique will be proposed.

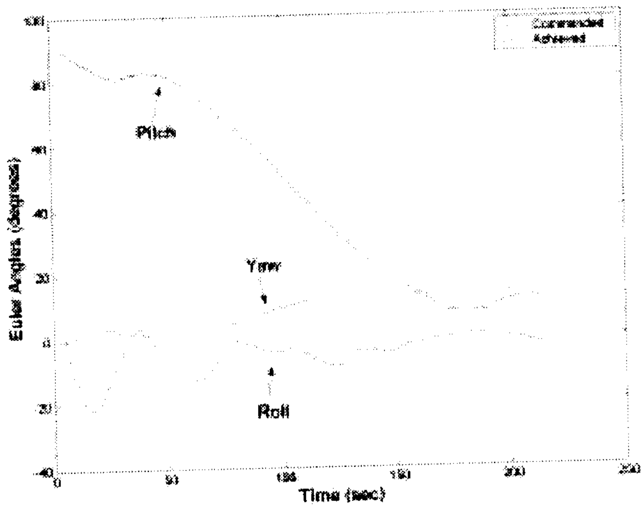

Figure 2. Attitude tracking response with instantaneous inner loop

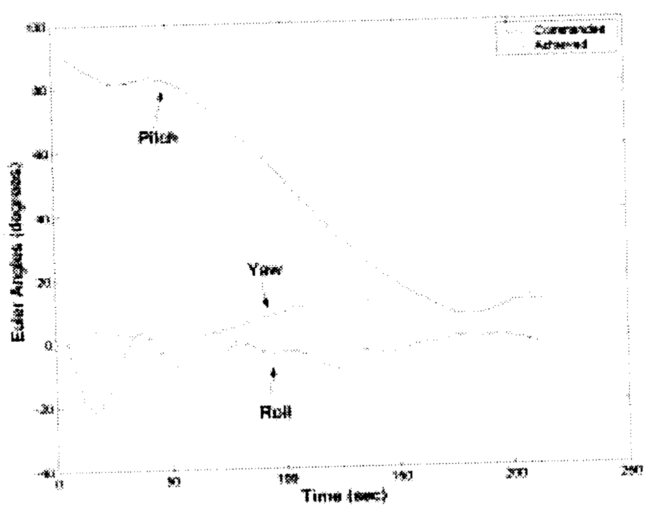

Figure 3. Attitude tracking response without torque saturation

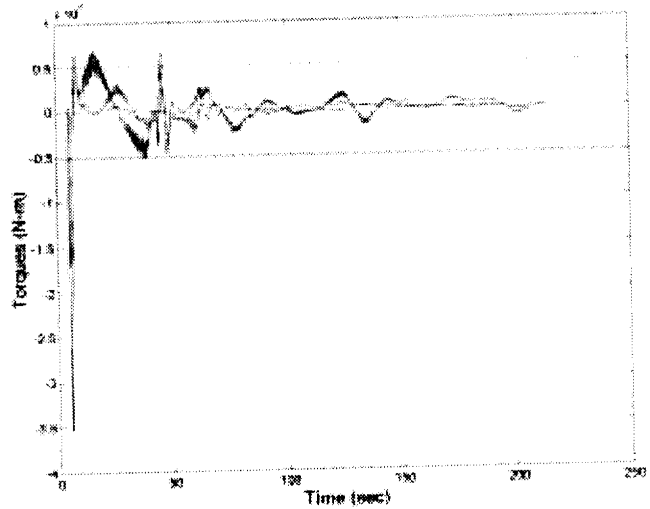

Figure 4. Achieved torque response without torque saturation

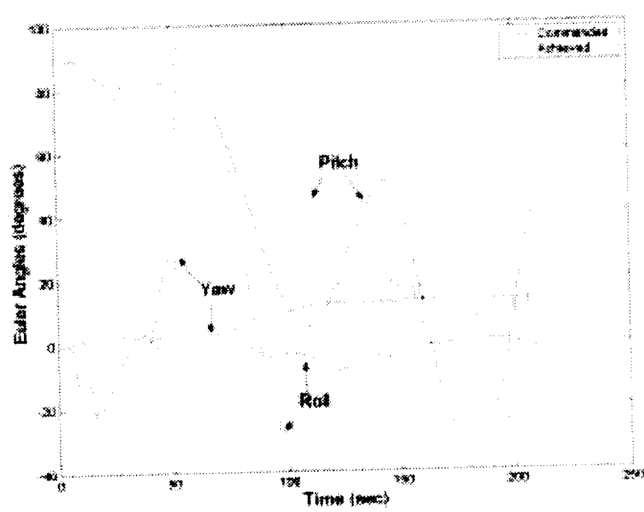

Figure 5. Attitude tracking response with torque saturation but without gain adaptation

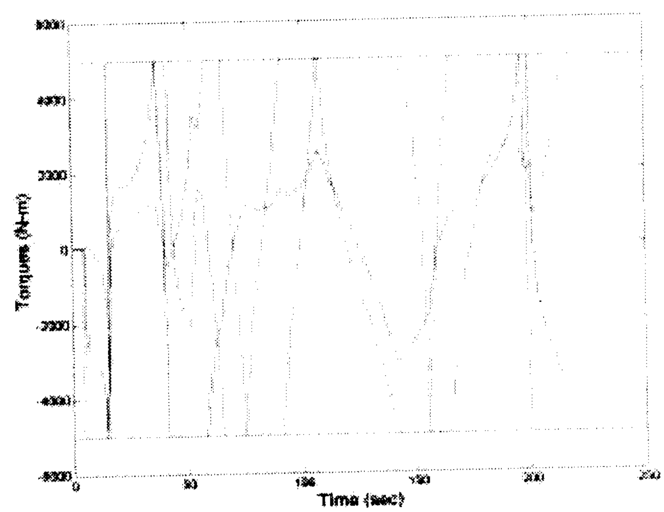

Figure 6. Achieved torque response with torque saturation but without gain adaptation

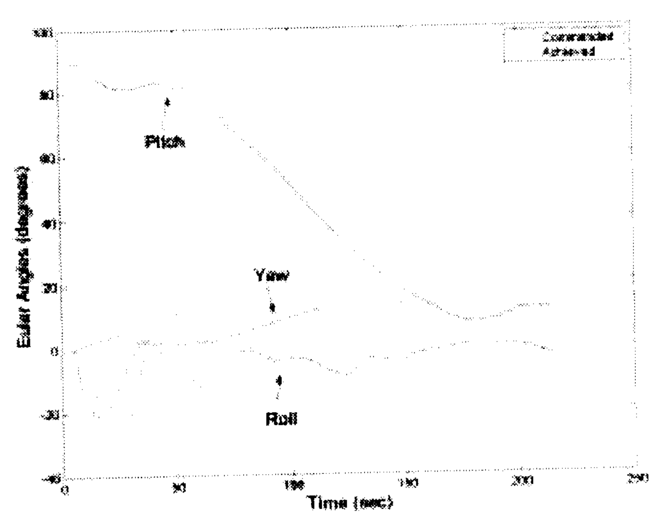

Figure 7. Attitude tracking response with torque saturation and gain adaptation

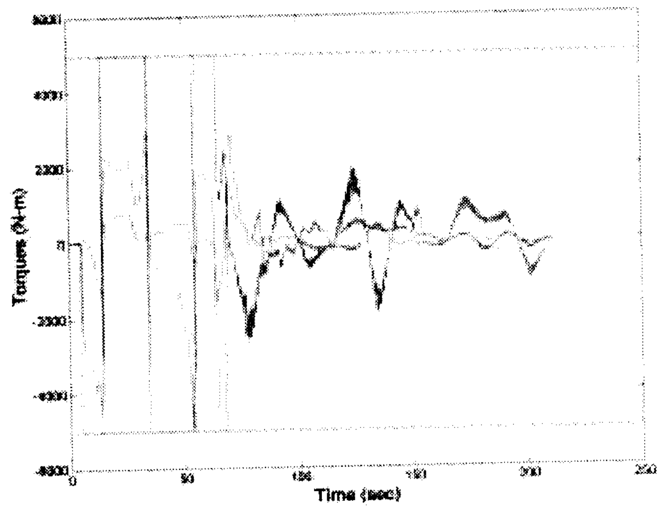

Figure 8. Achieved torque response with torque saturation and gain adaptation

References

[Bab96] Babcock, Philip S. IV (Charles Stark Draper Lab, Inc), Channelization: the two-fault tolerant attitude control function for the space station freedom, IEEE Aerospace and Electronic Systems Magazine, v11, n5, May, 1996 IEEE, Piscataway, NJ, USA, p 9-16, ISSN: 0885-8985 CODEN: IESMEA

[Bar92] Barry, John M. (Rockwell Int Corp), Simplified control and display concepts for space vehicle control, applied to space station, space shuttle and unmanned satellites, Advances in the Astronautical Sciences, Proceedings of the 15th Annual Rocky Mountain Guidance and Control Conference, Feb 8-12 1992, 1992, Keystone, CO, USA

[BC01] Bajpai, G. and B.-C. Chang (2001). Decoupling of failed actuators in flight control systems. Proceedings of the 2001 American Control Conference, Arlington , VA , pp. 1836 – 1840.

[BDR95] Brown, G. Mark (California Inst of Technology) Bernard, Douglas E. Rasmussen, Robert D., Attitude and articulation control for the Cassini spacecraft: a fault tolerance overview, IEEE/AIAA Digital Avionics Systems Conference - Proceedings, Proceedings of the 1995 AIAA/IEEE 14th Digital Avionics Systems Conference, DASC, Nov 5-9 1995, 1995, Cambridge, MA, USA

[BGM99] Boskovic, Jovan D. (Scientific Systems Co, Inc) Gopinathan, Murali Mehra, Raman K., Computer aided design of failure detection and identification and adaptive reconfigurable control systems for aerospace applications, Proceedings of the IEEE International Symposium on Computer-Aided Control System Design, Proceedings of the 1999 IEEE International Symposium on Computer Aided Control System Design, Aug 22-Aug 27 1999, 1999, Kohala Coat-Island, HI, USA

[BLM00] Boskovic, Jovan D. (Scientific Systems Co, Inc) Li, Sai-Ming Mehra, Raman K., Fault tolerant control of spacecraft in the presence of sensor bias, Proceedings of the American Control Conference, 2000 American Control Conference, Jun 28-Jun 30 2000, 2000, Chicago, IL, USA

[BLM01] Boskovic, J. D., S.-M. Li, and R. K. Mehra (2001). Robust supervisory fault-tolerant control system. Proceedings of the 2001 American Control Conference, Arlington , VA , pp. 1815 – 1820.

[CR94] Copeland, Robert P. (Wright State Univ) Rattan, Kuldip S., Fuzzy logic supervisor for reconfigurable flight control systems, IEEE Proceedings of the National Aerospace and Electronics Conference, Proceedings of the IEEE 1994 National Aerospace and Electronics Conference (NAECON 1994). Part 1 (of 2), May 23-27 1994 , 1994, Dayton , OH , USA

[FT90] Fernandez, Manny (Litton Systems, Inc, Woodland Hills, CA, USA) Tazartes, Daniel A., A fault-tolerant architecture for launch vehicle guidance and control--I: Requirement/architecture, 9th Digital Avionics Systems Conference, Oct 15-18 1990, 1990, Virginia Beach, VA, USA

[HC97] Hu, Changhua (Xi'an Research Inst of High Technology) Chen, Xinhai, Retaining fairly good performance of flight vehicle in case of partial failure of actuator, Xibei Gongye Daxue Xuebao/Journal of Northwestern Polytechnical University, v 15, n 4, 1997 NPU, Xi'an, China, p 563-569, ISSN: 1000-2758 CODEN: XGDUE2

[HSC00] Hess, R.A. (Univ of California, Davis) Siwakosit, W. Chung, J., Accommodating a class of actuator failures in flight control systems, Journal of Guidance, Control, and Dynamics, v23, n3, May-Jun, 2000 AIAA, Reston, VA, USA, p 412-419, ISSN: 0731-5090 CODEN: JGCODS

[JL00] Jonckheere, Edmond (Univ of Southern California) Lohsoonthorn, Poonsuk, Geometric approach to model matching reconfigurable propulsion control, Proceedings of the American Control Conference, 2000 American Control Conference, Jun 28-Jun 30 2000, 2000, Chicago, IL, USA

[Kha96] Hassan K. Khalil, Nonlinear Systems, 2nd Ed., Prentice Hall, 1996;

[MAG+89] Manjunatha, R. Agrawal, V. Goel, P. Malik, N. Rashinkar, P. Rao, K., Fault-tolerant system for attitude and orbit control of Insat II spacecraft, AIAA Computers in Aerospace VII Conference, AIAA Computers in Aerospace VII Conference, Oct 3-5 1989, 1989, Monterey, CA, USA

[PTD92] Pordon, R. (Guidance & Control Systems) Tompetrini, K. Weinstein, S. Dhuyvetter, H., New guidance and flight control system for the DELTA II launch vehicle, Advances in the Astronautical Sciences, Proceedings of the 16th AAS Rocky Mountain Guidance and Control Conference, Feb 6-10 1992, 1993, Keystone, CO, USA

[Rau94] Rauch, Herbert E. (Lockheed Palo Alto Research Lab), Intelligent fault diagnosis and control reconfiguration, IEEE Control Systems Magazine, v 14, n 3, Jun, 1994, p 6-12, ISSN: 0272-1708 CODEN: ISMAD7

[SWM+01] Schierman J. D., D. G. Ward, J. F. Monaco and J. R. Hull (2001). A reconfigurable guidance approach for reusable launch vehicles. *AIAA guidance, navigation and control conference and exhibit*, Paper No. AIAA-2001-4429, Montreal, Canada.

[SZD02] Yuri. B. Shtessel, J. Jim Zhu and Dan Daniels, "Reusable Launch Vehicle Attitude Control Using A Time-Varying Sliding Mode Control Technique," Submitted for review in this invited session.

[VD01] Venkataraman, R. and D. B. Doman (2001). Control allocation and compensation for over-actuated systems with nonlinear effectors. Proceedings of the 2001 American Control Conference, Arlington , VA , pp. 1812 – 1814.

[VM96] Vos, David W. (Aurora Flight Sciences Corp., Hood River, OR, USA) Motazed, Ben, Application of fault-tolerant controls to UAVs, Proceedings of SPIE - The International Society for Optical Engineering, Navigation and Control Technologies for Unmanned Systems, Apr 8-9 96, 1996, Orlando, FL, USA

[WGW99] Wu, Shu-Fan (Nanjing Univ of Aeronautics and Astronautics) Grimble, Michael J. Wei, Wei, QFT based robust/fault tolerant flight control design for a remote pilotless vehicle, IEEE Conference on Control Applications - Proceedings, v1, 1999 IEEE, Piscataway, NJ, USA, p 57-62 CODEN: ICOAE8

[WSK+00] Wills, Linda (Georgia Inst of Technology) Sander, Sam Kannan, Suresh Kahn, Aaron Prasad, J.V.R. Schrage, Daniel, Open control platform for reconfigurable, distributed, hierarchical control systems, AIAA/IEEE Digital Avionics Systems Conference - Proceedings, 19th Digital Avionics Systems Conference (DASC), 2000, Philadelphia, PA, USA

[ZBH00] J. Jim Zhu, Brad D. Banker, Charles E. Hall, "X-33 Ascent Flight Controller Design by Trajectory Linearization- A Singular Perturbational Approach," 2000 AIAA Guidance, Navigation, and Control Conference, Denver, CO, Aug. 2000.

[ZHF+01] J. Jim Zhu, A. Scott Hodel, Kerry Funston and Charles E. Hall, "X-33 entry flight controller design by trajectory linearization – a singular perturbational approach," Proceedings, American Astronautical Society Guidance and Control Conference, Breckenridge, Colorado, pp. 151-170, Jan. 2001.

[ZM98] J. Zhu and M. C. Mickle, "Synthesis of time-varying bandwidth filters based on all-pole LTI prototypes," Proceedings, American Control Conference, Philadelphia, PA, 2889-2894, June, 1998.

[Zhu98] J. Jim Zhu, Nonlinear Tracking and Decoupling by Trajectory Linearization, Lecture Note, Presented at NASA Marshall Space Flight Center, 137 pp., June 1998.