

# Multiple-Model Adaptive Fault-Tolerant Control of a Planetary Lander

Jovan D. Bošković,\* Joseph A. Jackson,† and Raman K. Mehra‡  
*Scientific Systems Company, Inc., Woburn, Massachusetts 01801*

and

Nhan T. Nguyen§  
*NASA Ames Research Center, Moffet Field, California 94035*

DOI: 10.2514/1.42719

**In this paper we present an approach to fault-tolerant control based on multiple models, switching, and tuning and its implementation to a hardware-in-the-loop simulation of Delta Clipper Experimental dynamics. The Delta Clipper Experimental is characterized by large control input redundancy, which made it an ideal test bed for evaluation of advanced fault-tolerant and adaptive reconfigurable control strategies. The overall failure detection, identification, and accommodation architecture is an upgraded version of our Fast Online Actuator Reconfiguration Enhancement (FLARE) system. The FLARE approach is based on representing different possible fault and failure scenarios using multiple observers, such that the case of nominal (no-failure) operation is covered along with the loss-of-effectiveness, lock-in-place, and hardover failures of the flight control effectors. Based on a suitably chosen performance criterion, the FLARE system quickly detects single or multiple failures and reconfigures the controls, thus achieving either the original desired performance or graceful performance degradation. In the first stage of the project, the FLARE system was tested on a medium-fidelity simulation of Delta Clipper Experimental dynamics, resulting in excellent performance over a large range of single and multiple faults and failures. Following that, in collaboration with Boeing Phantom Works, the FLARE run-time code was installed at their site and tested on a hardware-in-the-loop test bed consisting of an electromechanical actuator actuating a gimballed engine as a part of a simulation of the Delta Clipper Experimental dynamics. A large number of hardware-in-the-loop simulations were run to cover a dense test-case matrix, including cases of up to 10 simultaneous control effector failures. In all cases FLARE was able to quickly and accurately detect the failures and reconfigure the controls, resulting in excellent overall system performance. In this paper we describe the Delta Clipper Experimental and its dynamics model, along with the multiple models, switching, and tuning based modification of our FLARE system. This is followed by a description of the experimental test bed and a discussion of the results obtained through hardware-in-the-loop testing.**

## Nomenclature

$a$	= lateral distance from engines to c.g., m
$b$	= longitudinal distance from engines to c.g., m
$c$	= lateral distance from thrusters to c.g., m
$c_1, c_2$	= performance index gains
$d$	= longitudinal distance from thrusters to c.g., m
$F_{ab}$	= force along $a$ axis due to actuator $b$ , N
$G_o$	= nonlinear control derivative matrix
$g$	= acceleration due to gravity, $9.81 \text{ kg} \cdot \text{m}/\text{s}^2$
$I_j(t)$	= performance index of estimator $j$ at time $t$
$J, J_{ii}$	= inertial matrix, elements with $J_{xx}, J_{yy}$ , and $J_{zz}$ on the diagonal, $\text{kg}/\text{m}^2$
$K, k_i$	= loss-of-effectiveness failure diagonal matrix, $i$ th value
$m$	= mass, kg
$P_i$	= magnitude of $i$ th reaction control system thruster, N

$r_{ab}$	= component along $a$ axis of the $b$ th reaction control system thruster, m
$r_{(\cdot)}$	= commands for the reference trajectory, m/s
$T_i$	= thrust magnitude from engine $i$ , N
$t_{Fi}$	= time of failure injection on actuator $i$ , s
$\mathbf{u}$	= control inputs, $u_1-u_4$ : engine thrust, N; $u_5-u_{12}$ : gimbal angles, rad; $u_{13}-u_{16}$ : thrust from reaction control system, N
$\mathbf{u}_c$	= commanded control input vector
$\mathbf{x}$	= system state
$x, y, z$	= position coordinates in the inertial frame, m
$\alpha_{Ri}$	= radial angle of $i$ th engine gimbal, rad
$\alpha_{Ti}$	= tangential angle of $i$ th engine gimbal, rad
$\gamma$	= estimator adaptation gain
$\Delta, \delta$	= normalization matrix, factor
$\Theta, \theta_i$	= lumped failure parameter diagonal matrix, $i$ th value
$\Lambda, \lambda_i$	= actuator gain diagonal matrix, $i$ th value, $1/\text{s}$
$\Sigma, \sigma_i$	= lock-in-place failure diagonal matrix, $i$ th value
$\tau_{ab}$	= torque about $a$ axis due to actuator $b$ , Nm
$\omega$	= attitude vector, $[\phi, \theta, \psi]^T$ , rad

Presented as Paper 7290 at the AIAA Guidance, Navigation and Control Conference and Exhibit, Honolulu, HI, 18–21 August 2008; received 23 January 2009; revision received 18 August 2009; accepted for publication 20 August 2009. Copyright © 2009 by Scientific Systems Company, Inc.. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission. Copies of this paper may be made for personal or internal use, on condition that the copier pay the \$10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0731-5090/09 and \$10.00 in correspondence with the CCC.

\*Intelligent & Autonomous Control Systems Group Leader, 500 West Cummings Park, Suite 3000; jovan@ssci.com. Senior Member AIAA.

†Research Engineer, Intelligent & Autonomous Controls Systems, 500 West Cummings Park, Suite 3000; jjackson@ssci.com. Member AIAA.

‡President and CEO, 500 West Cummings Park, Suite 3000; rkm@ssci.com. Member AIAA.

§Principal Research Scientist, Mail Stop 269-4; Nhan.T.Nguyen@nasa.gov. Associate Fellow AIAA.

## I. Introduction

**I**N THE recent past there has been much interest in the design and implementation of failure detection, identification, and reconfiguration (FDIR) techniques to aerospace vehicles under subsystem and component failures and damages [1–5]. Although many of the proposed techniques have been demonstrated as effective control reconfiguration strategies for accommodation of different types of failures and damages in aerial vehicles, space vehicles such as planetary landers have attracted comparably less attention in the existing literature.