

Practical Steering Law for Small Satellite Energy Storage and Attitude Control

David J. Richie* and Vaios J. Lappas†

University of Surrey, Guildford, England GU2 7XH, United Kingdom
and

Bong Wie‡

Iowa State University, Ames, Iowa 50011-2271

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Recent practical work in developing combined energy storage and attitude control subsystems for small satellites has opened the door to more complex, demanding space missions. Laden with substantial benefits, these efforts use variable-speed control moment gyroscopes to store and drain energy while controlling satellite orientation. The full nonlinear equations for simultaneous control of gimbal and wheel motors for this system were theoretically unraveled in previous work but assumed that a single computer dictates the commands to these motors at each time step. This method renders it impossible to control the wheel and gimbal motors separately: a requirement for immediate flywheel implementation in contemporary satellite energy storage subsystems. Such isolated flywheel control would impart disturbance torques from torquing the wheel motors through passive electronic circuits. This torque then must be accommodated by the gimbal steering law, which is also tasked with slewing the satellite. To address this need, a novel gimbal steering law is derived to permit independent gimbal and wheel control of the actuators with continued singularity avoidance: a situation that allows direct incorporation of such a system into an existing small satellite energy storage subsystem.

Nomenclature

$D^\#$	= suitable pseudoinverse logic for matrix D
e	= variable-limiter proportional-plus-integral-plus-derivative integral error matrix
G	= generalized singularity robust dither matrix
H_x, H_y, H_z	= control-moment-gyroscope angular momentum in three dimensions, $\text{N} \cdot \text{m} \cdot \text{s}$
h	= angular momentum, $\text{N} \cdot \text{m} \cdot \text{s}$
$I_{W_{s_d}}$	= diagonal gyro wheel spin-axis inertia matrix, $\text{kg} \cdot \text{m}^2$
I_{G_j}, I_{W_j}, I_{sc}	= gimbal, wheel, and satellite bus inertia matrices, $\text{kg} \cdot \text{m}^2$
n	= number of cluster actuators
P_e	= power tracking error, W
$q(\beta)$	= matrix function of attitude quaternion β
V	= wheel spin-axis momentum matrix
β_e	= largest quaternion error (measured at each time step)
θ	= control-moment-gyroscope pyramid angle, deg
κ	= control-moment-gyroscope singularity index
μ, μ_2	= variable-speed control-moment-gyroscope pseudoinverse singularity avoidance exponent
$\bar{\Omega}, \bar{\Omega}$	= estimated wheel speed, wheel acceleration
$\bar{\Omega}$	= maximum wheel acceleration, rad/s^2

Ω_j = j_{th} wheel speed, rad/s

Subscripts

a	= actual
c	= command, commanded
d	= disturbance (e.g., attitude torque)
g	= control-moment-gyro gimbal axis
i	= i_{th} object (e.g., $i = 1, 2, 3, 4$ or $i = 1, 2, 3$)
j	= j_{th} object (e.g., $j = 1, 2, 3, 4$ or $j = 1, 2, 3$)
m	= measured value (e.g., attitude orientation, rate)
r	= reference or required
s	= control-moment-gyro spin axis
sc	= spacecraft (satellite)
t	= control-moment-gyro transverse axis
w, wh	= wheel (rotor, shaft, and motor)
(0)	= initial condition value (e.g., initial wheel speed)
1, 2a, 2b	= steering-law identifiers

I. Introduction

BECAUSE OF advancing technology and miniaturization, today's small satellites (less than 500 kg) are increasingly used for more complex missions. One method that enables this complexity increase at reduced mass is combining subsystems. Combined energy storage and attitude control subsystems (ESACS) achieve this need through consolidating actuator components. Specifically, flywheel-based momentum-exchange devices can be used not only in traditional satellite pointing control roles but also as dynamos to store primary source energy (e.g., from solar arrays) then drain it, passing secondary power to the satellite's subsystems during eclipse. This assumes that minimal energy is maintained in these flywheel batteries such that these actuators can provide adequate pointing control while serving as dynamos. Three basic momentum-exchange actuator approaches can satisfy this ESACS concept: counter-rotating flywheels, redundant flywheel clusters (e.g., at a minimum for three-axis control this implies at least four wheels in a tetrahedron), and variable-speed control moment gyroscopes (VSCMGs). The term ESACS is used here instead of the older integrated power and attitude control subsystem (IPACS), as an IPACS implies that simultaneous (i.e., integrated) command solutions are sent to the attitude and power

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*Major, U.S. Air Force; Ph.D. Graduate, Surrey Space Centre, School of Electronics and Physical Sciences; d_j_richie@yahoo.com. Senior Member AIAA.

†Senior Lecturer, Surrey Space Centre, School of Electronics and Physical Sciences; v.lappas@surrey.ac.uk. Member AIAA.

‡Professor, Department of Aerospace Engineering; bong.wie@iastate.edu. Associate Fellow AIAA.