REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

0272

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
1 Sep 2000 - 31 Jan 2004

4. TITLE AND SUBTITLE
Nonlinear Spacecraft Control With Applications to Combined Attitude and Energy Storage

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-00-1-0374

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Georgia Institute of Technology
Atlanta, GA 30332-0150

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
4015 Wilson Blvd
Mail Room 713
Arlington, VA 22203
NM

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; Distribution is Unlimited.

20040602 097

13. SUPPLEMENTARY NOTES

14. ABSTRACT
F49620-00-1-0374. The period of performance for this research award was from August 2000 to January 2004.
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Panagiotis Tsiotras
U	U	U	UU		19b. TELEPHONE NUMBER *(Include area code)*

Nonlinear Spacecraft Control With Applications To Combined Attitude And Energy Storage

Final Report
AFOSR Grant Number F49620-00-1-0374

by

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April 2004

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NONLINEAR SPACECRAFT CONTROL WITH APPLICATIONS TO COMBINED ATTITUDE AND ENERGY STORAGE

Final Report

AFOSR Grant Number F49620-00-1-0374

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Executive Summary

Therein we summarize the research results developed under AFOSR Grant number F49620-00-1-0374. The period of performance for this research award was from August 2000 to January 2004. The main objective of this research was to support the Air Force efforts in the development of an Integrated Power and Attitude Controls System (IPACS) for spacecraft applications. An IPACS will combine the attitude control and power distribution subsystems onboard a spacecraft, reducing the bus mass, and thus leading to increased payload. Several options for IPACS have been investigated in this work including clusters of momentum wheels and variable-speed control moment gyros. The latter seem to be ideally suited for IPACS applications since they naturally decompose the power storage/release function using the wheel acceleration, and the attitude control function using the gimbal acceleration. Consequently, the focus of this research has thus been confined to the use of VSCMGs. Several practical and theoretical issues were encountered and were successfully addressed. The problem of singular configurations during the operation of a VSCMG cluster has been completely analyzed. A simple design criterion has been proposed to size the flywheels so no inescapable singularities occur. For escapable singularities appropriate control laws have been designed. Experimental results have been obtained via a high-fidelity spacecraft simulator facility that was designed and developed with the help of an accompanying DURIP/AFOSR award.

Flywheels used in an IPACS typically need to spin at very high speeds (more than 60,000 rpm) in order to be competitive with chemical batteries. At such high speeds the shaft/flywheel flexibility effects may lead to instability. Uncertainties in the natural frequencies and material damping complicate the whole control design. Robust control laws for highly-flexible flywheel systems have been designed and implemented. In addition, flywheels used in an IPACS should have low electromechanical losses. Mechanical losses can be eliminated with the use of active magnetic bearings. Elimination of magnetic and electrical losses in the magnetic bearings on the other hand requires novel nonlinear control laws. Such control laws have been developed and implemented on a test-rig designed specifically for that purpose under the collaboration with the AFRL/VS.

An Educational Partnership Agreement (EPA) was established between Georgia Tech and AFRL/VS. As part of this EPA, two Georgia Tech graduate students participated in the Space Scholars program at AFRL/VS at Kirtland AFB, Albuquerque for two consecutive.

As a result of the support received from this award, two students received their Ph.D. degrees and five students received their MS degrees. Twenty-three papers and three patents (one awarded, two pending) document the results of this work.

Contents

1 Introduction

1.1 Research Objectives and Summary of Accomplishments

The main research objective of this work was the use of advanced concepts from nonlinear control theory to assist with the development of an integrated power and attitude control system (IPACS) for future spacecraft. All aspects which are imperative for a successful design of an IPACS have been investigated, including choice of actuators (MW of VSCMG), singularity avoidance, low-loss active magnetic bearing control and robust control of high-speed flywheels. Experimental validation of the theoretical results has also been achieved.

As part of this program we have developed novel attitude control laws for spacecraft and satellites in orbit, emphasizing integrated attitude control and power management using flywheels. We have also addressed issues specific arising from actuator failures and the use of Variable Speed Control Moment Gyros (VSCMG's) as torque actuators. Specifically, we developed control laws for an Integrated Power and Attitude Control System (IPACS) using momentum wheels (MW's) or VSCMG's in several configurations. We investigated singularity-avoidance control laws associated with the use of VSCMG's as well as implementation issues, such as robustness with respect to inertia parameters and actuator saturation. We implemented the developed control algorithms in a realistic environment. This was done using an air-bearing spacecraft simulator facility developed with the help of the AFOSR/DURIP award F49620-01-1-0198.

Associated with the use of VSCMG's as dual actuators for attitude control and energy storage on-board spacecraft is the design of robust, low-loss control laws for Active Magnetic Bearings (AMB's) to support high-speed flywheels. We have developed such control laws using a novel AMB voltage switching scheme, also accounting for voltage saturation. These theoretical results were experimentally validated on a specifically constructed test-rig. This part of the work was directly supported by the AFRL/VS directory. The point of contact in AFRL/VS was Dr. Jerry Fausz.

1.2 Goals of this Report

The main goal of this report is to summarize the results obtained under this research program. Since most of the technical results have appeared or will soon appear in over 26 archival journal and conference publications, below we only summarize these results and remark on their significance and their interrelationship.

2 Description of Work Accomplished

The following research accomplishments were achieved over the duration of this project (August 2000–January 2004).

2.1 Control of Underactuated Spacecraft

The current and future trend in spacecraft operations is to move from the large, complex satellites to clusters of smaller, smarter spacecraft. In order to keep the size and cost down, commercial, off-the shelf components must be used, whenever possible. Often, whole subsystem components are eliminated completely and redundant components are kept to a minimum. The use of commercial, non space-certified equipment, without the benefit of back-up subsystems, results to an increased potential for failure. The underactuated spacecraft control problem is very difficult because standard nonlinear techniques cannot be used.

We have proposed non-smooth control laws that avoid the use of periodic, highly oscillatory control inputs reported previously in the literature that may be unacceptable for spacecraft with flexible components. As a matter of fact, all proposed control laws avoid excessive oscillations and achieve asymptotic stability with exponential convergence. In [2] we considered the problem of attitude and angular velocity stabilization of a rigid spacecraft, which is almost axisymmetric about its body 3-axis. A small parameter ϵ gives a measure of the non-symmetry of the spacecraft about this axis. A control law was introduced for a special subsystem of the complete dynamical system under consideration. This control law can be used either alone for detumbling maneuvers of nearly symmetric spacecraft, or as part of a more general control strategy to stabilize the complete attitude of non-symmetric spacecraft. Our research in the area of underactuated spacecraft was summarized in [8]. Therein we have presented a series of new results for the problems of detumbling with simultaneous attitude stabilization about the unactuated axis, the complete attitude stabilization problem, and the feasible trajectory generation problem for a *non-symmetric* spacecraft with one actuator failure. For the non-symmetric case, in particular, we have used the method of averaging to construct a system that approximates the original system. We have shown that the averaged system is differentially flat by explicitly computing its flat outputs. We have used these flat outputs to generate feasible trajectories that can be tracked exactly by the underactuated spacecraft.

2.2 Attitude Control and Power Tracking using Flywheels

Space vehicle programs consistently seek to reduce satellite bus mass to increase payload capacity and/or reduce launch and fabrication costs. In addition, satellite system performance demands continually challenge space vehicle designers. Flywheel-based systems providing both energy storage and attitude control address the requirement of reducing the satellite bus mass by combining subsystem functionality. Such IPACS systems are currently under investigation by the Air Force, NASA and private industry.

In [5,16], four or more energy/momentum wheels in an arbitrary non-coplanar configuration, and a set of three thrusters are used to implement an IPACS scheme. The energy/momentum wheels are used as attitude control actuators, as well as an energy storage mechanism, providing power to the spacecraft. The thrusters are used to implement the torques for large and fast (slew) maneuvers during the attitude initialization and target acquisition phases and to implement the momentum management strategies. The energy/momentum wheels provide the reference-tracking torques and the torques for spinning up or down the wheels for storing and releasing kinetic energy. One of the main issues in the control design for an IPACS is that the power and attitude tracking be performed simultaneously and independent of one another. We insist on this separation of objectives since it is unlikely that any IPACS system which compromises either power or attitude control requirements will be acceptable for routine spacecraft operations. In order to achieve this, the torques applied by the energy/momentum wheels are decomposed into two spaces which are orthogonal to each other. The possibility of occurrence of singularities – where no arbitrary energy profile can be tracked – is studied for a generic wheel cluster configuration. A standard momentum management scheme is considered to null the total angular momentum of the wheels so as to minimize the gyroscopic effects and prevent the singularity from occurring.

2.3 Adaptive Attitude Control and Power Tracking using VSCMG's

The single-gimbal control moment gyro (CMG) has been studied as a spacecraft reorientation actuator for a long time due to its torque amplification effect. However, a single-gimbal CMG has a critical drawback in the sense that there exists geometric singularities for which, when encountered, the CMG cannot generate the commanded torque. One method to overcome this drawback of a CMG is the use of a Variable Speed single-gimbal Control Moment Gyro (VSCMG). While the wheel spin of a conventional CMG is constant,the VSCMG is allowed to have variable speed. Therefore, a VSCMG has extra degrees of freedom which can be used to achieve additional objectives, such as energy storage and/or singularity avoidance, as well as attitude control.

In [1,6,7,9,12] we developed control laws for coordinated attitude control with power storage and distribution on-board a spacecraft using variable-speed control moment gyros (VSCMGs). VSCMGs seem to be particularly appealing as IPACS actuators since they can use the gimbal and spin axis degrees of freedom to effectively decouple the tasks of attitude control and of energy storage. Moreover, VSCMGs can take advantage of the torque amplification property (as the common CMGs) to generate large torques. References [1,9] and [12] developed the complete equations of motion for a spacecraft with N VSCMGs. In [12] we developed both model-based and adaptive IPACS algorithms using VSCMGs. The latter do not assume any knowledge of the moment of inertia matrix of the spacecraft. In order to avoid any wheel speed saturation or complete despin of the wheels, these control algorithms were augmented with a "hard" and a "soft" wheel equalization strategies. These "plug-in" controllers can be used to keep the wheel speed exactly or approximately equal, respectively, without compromising the other operational requirements. See Fig. 1. Alternatively, coordinated action between the thrusters and the wheels can be used to damp the excess momentum of the wheels if needed [16]. A SIMULINK-based software tool (the "The VSCMG Workbench"), has been developed in [7] for simple and quick implementation of VSCMG cluster geometry and IPACS control laws. The program uses a modularized structure that permits flexibility in implementation. It is composed of several modules, each having several layers of detail.

It should be pointed out that this research has led to the development of patented results. Specifically, two patents based on these IPACS algorithms have been applied for via the Georgia Tech Research Corporation.

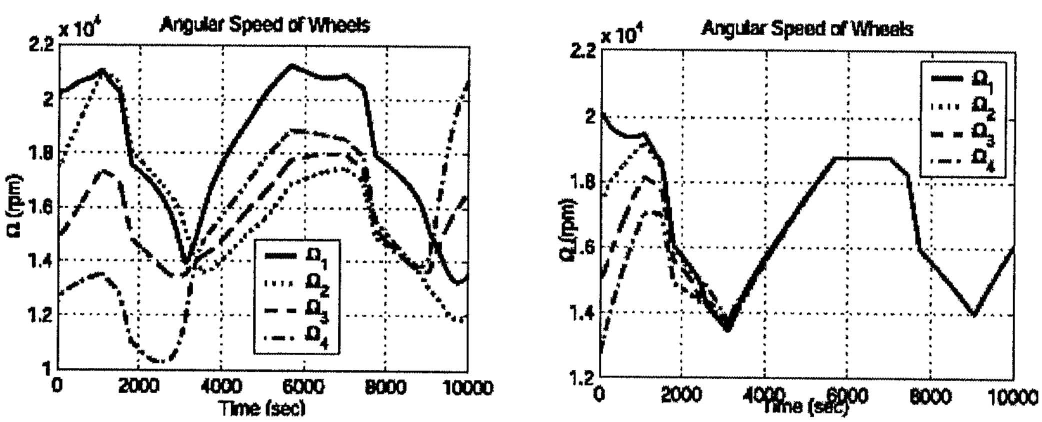

Figure 1: Control with wheel speed equalization strategy (right) and without (left). From [21].

2.4 Singularity Classification and Avoidance for VSCMGs

While the gimbal rates are the only control input variables in a CMG system, the wheel accelerations offer additional control variables in the case of a VSCMG system. If there are at least two wheels and their (fixed) gimbal axes are not parallel to each other, and if none of the wheel speeds becomes zero, then such a VSCMG system can generate control torques along arbitrary directions and never falls into singularities. However, in practice, it is still desirable to generate the required torques using gimbal angle changes rather than wheel speed changes. Hence, we may define as a "singularity of a VSCMG cluster" the rank deficiency of the matrix gimbal rate coefficient matrix, even though the VSCMGs are able to generate an arbitrary torque at such cases.

The singular manifold for a CMG or VSCMG is defined as the set of gimbal angles such that the commanded torque (or power) cannot be followed exactly. This is the locus (surface) of all angular momentum states such that the CMG cannot generate a torque along the normal direction to this surface. For a pyramid configuration with four wheels, the angular momentum envelope of a CMG consists of two types of singular surfaces which are connected to each other smoothly. Figure 2(a) shows the singular surface for the first singularity type. This singular surface does not cover the whole momentum envelope and there are holes on the surface. These holes are smoothly connected to the second type of the singular surface which is a trumpet-like funnel inside the envelope. Figure 2(b) shows the latter surface which consists of two portions: the external portion, which is part of the envelope, and the internal portion, which lies entirely inside the momentum envelope.

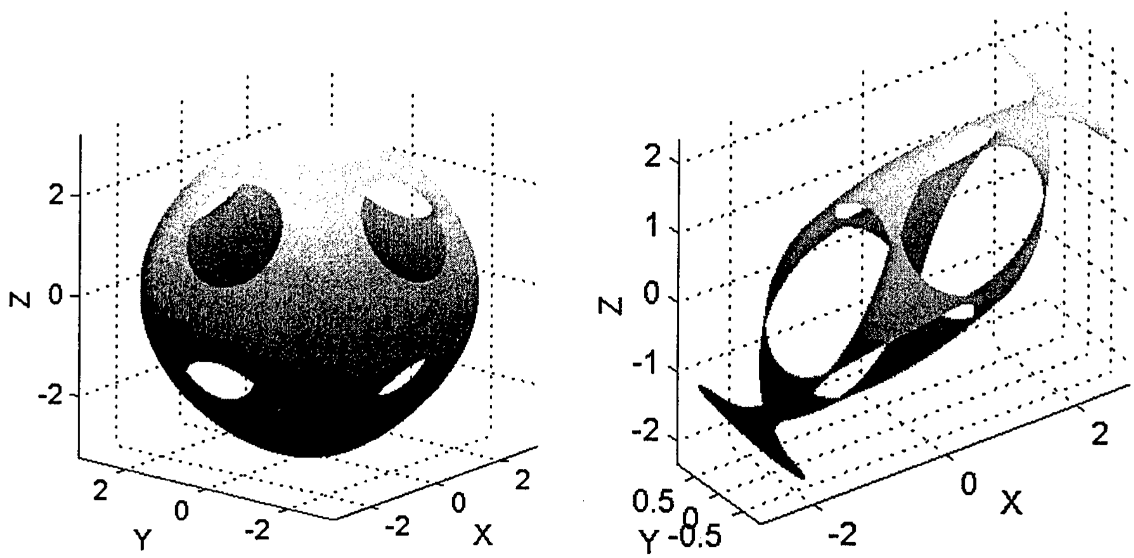

Figure 2: The two types of singular surfaces for a CMG cluster in a pyramid configuration (4 CMGs).

A null motion strategy has been developed in [12] and used to escape from certain singular states. These states are called *'indefinite'*, *'hyperbolic'* or *'passable'*. However, there are also states that cannot be avoided by null motion. These singularities are called *'definite'*, *'elliptical'* or *'impassable'*. Any singularity avoidance method using null motion fails if the CMG encounters a singular state of the latter type. Every state on the envelope shown in Fig. 2(a) is elliptically singular; some of internal singularities of Fig. 2(b) are elliptical, as well.

More challenging is the singularity analysis of a VSCMG cluster with power tracking. In this case, the occurrence of escapable and inescapable singular configurations is completely characterized by the rank of the following matrix [21]

$$M \triangleq \begin{bmatrix} I_{\mathrm{ws}_1}\mathbf{u}^T\mathbf{s}_1 & I_{\mathrm{ws}_2}\mathbf{u}^T\mathbf{s}_2 & \cdots & I_{\mathrm{ws}_N}\mathbf{u}^T\mathbf{s}_N \\ I_{\mathrm{ws}_1}\Omega_1 & I_{\mathrm{ws}_2}\Omega_2 & \cdots & I_{\mathrm{ws}_N}\Omega_N \end{bmatrix} \tag{1}$$

where $\mathbf{s}_i$ is spin axis vector, I_{ws_i} is the axial moment of inertia and Ω_i is the speed of the i-th wheel. In (1) $\mathbf{u}$ denotes the singular direction vector. If rank $M = 2$ the singularity is escapable (a null motion strategy exists). Otherwise, the singularity is inescapable.

The null motion developed in [12,24] for escaping from hyperbolic singular states cannot be used for elliptic singularities. For elliptic singular states the best one can expect is to avoid them altogether by proper sizing of the wheels. In [21,25] we found a simple condition which can be used for this purpose. Simply put, this condition states that a VSCMG system used for both attitude and power tracking (in a standard pyramid configuration) will encounter an elliptic singularity in the interval $0 \leq t \leq t_f$ if and only if there exist $\bar{t} \in [0, t_f]$ such that

$$\|\mathbf{H}(\bar{t})\| \geqslant \sqrt{\frac{16}{3}E(\bar{t})I_{\mathrm{w}}}$$

where $E(t)$ is the given energy command history, $\mathbf{H}(t)$ is the angular momentum command history and I_{w} is the wheel polar moment of inertia. Extensive numerical examples have verified the theoretical prediction for necessity and sufficiency of this condition.

A geometrically elegant picture for the occurrence of singularities emerges with the introduction of three momentum envelopes: first, the momentum envelope for given wheel speeds (A), second the momentum envelope for given kinetic energy and gimbal angles (B), and third the momentum envelope for given kinetic energy (C). The interplay between these three envelopes determines the rank of the matrix M and thus, the encounter of singularities. The two cases are shown in Fig. 3. The calculation of the envelopes (B) and (C) requires the solution of a constrained maximization problem. The details are given in [21].

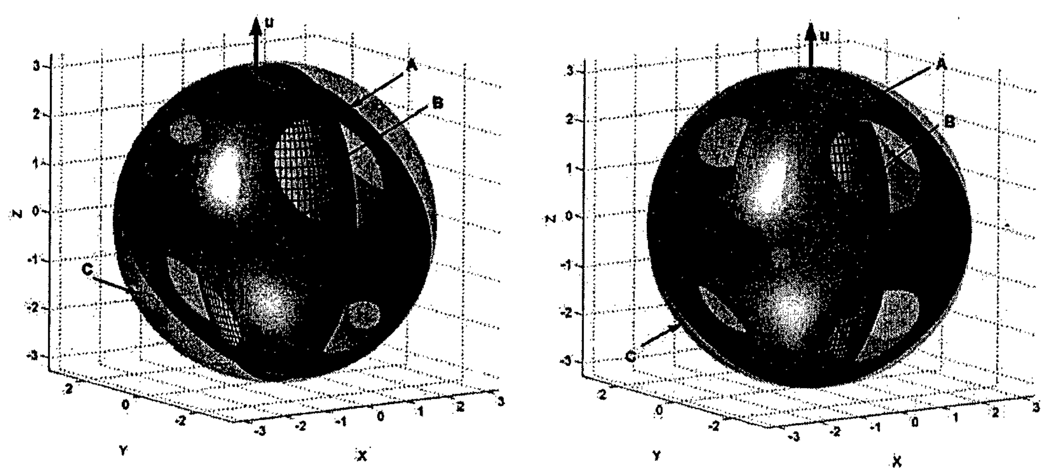

Figure 3: Escapable (left) and inescapable (right) singularity of a VSCMG cluster. From [21].

2.5 Spacecraft Stabilization using a Single VSCMG

The problem of spacecraft stabilization using less than three independent controls about the spacecraft body axes has been addressed in several papers. Most of these papers either assume thrusters or reaction wheels as actuators. Such devices provide control torques having constant direction in the body frame. Control moment gyros (CMG's) or variable speed CMG's (VSCMG's) provide torques that are *perpendicular* to a fixed spacecraft axis (the gimbal axis). Therefore, previous results in the literature cannot be used directly.

In [17] we have investigated the problem of spacecraft stabilization using a single VSCMG. Linearization of the equations of motion shows that complete attitude stabilization is not possible via linear methods. However further analysis shows that the linearized angular velocity equations are controllable, and a standard LQR control law has been used to locally asymptotically stabilize the angular velocity (detumbling). For global stabilization of the angular velocity vector, a nonlinear approach is required. Noticing that the system to be controlled satisfies a Jurdjevic-Quinn condition we have proposed a globally asymptotically stabilizing control law using a Lyapunov-based L_gV design. Numerical examples demonstrate the success of the method. Figure 4 shows a series of snapshots of a detumbling maneuver for a spacecraft with a single VSCMG.

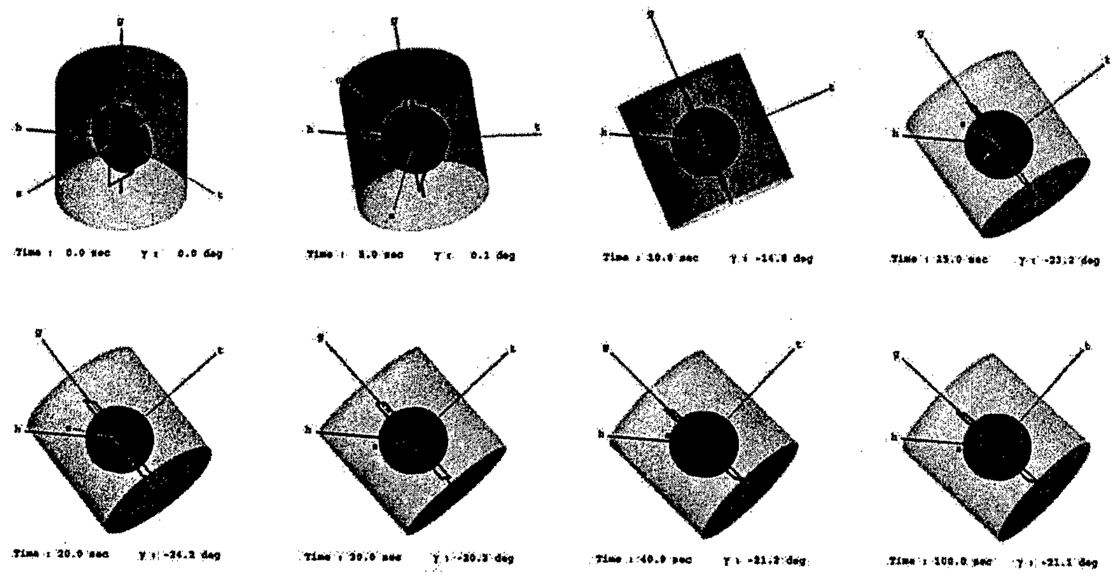

Figure 4: Series of snapshots of a detumbling maneuver of a spacecraft with a single VSCMG. From [17].

2.6 Robust Gain-Scheduled Control of High-Speed Rotors

An Energy-Momentum Wheel (EMW) is a flywheel that combines the functions of energy storage and momentum management into a single device. The successful application of EMWs to satellite systems, in particular, holds the promise of significantly reducing a satellite's mass and cost when contrasted with traditional satellite architectures that separate the energy storage and momentum management functions. Magnetic bearing technology is of crucial importance for efficient EMWs due to several advantages including operation at very high speed, no lubrication requirement, no wear and low power loss. In addition, spacecraft specifications often require stringent pointing requirements, as well as a vibration-free environment for on-board experiments. Imbalances and resonant modes in EMWs can create inertia forces which, when interacting with the stator, transmit unwanted vibration onto the spacecraft structure. This can be avoided with the use of AMBs coupled with an online controller that rejects undesirable vibrations. The successful development of effective magnetic bearing controllers is thus a critical technology for the use of EMWs in satellites.

Conventional control methodologies for flywheels supported on AMBs typically assume a Linear Time-Invariant (LTI) plant. This is a reasonable assumption if the speed of the rotor remains relatively constant. If, on the other hand, the speed of the rotor ranges over a wide spectrum of operating speeds (as is the case for EMWs) the LTI assumption is no longer valid. This is because the system matrix of these plants is a function of the rotor speed and the plant dynamics change considerably with rotor speed due to gyroscopic effects. Consequently, conventional control algorithms which do not give due consideration to the parameter varying nature of the plant often do not have the desired performance when they operate over a wide range of rotor speeds. The greatest difficulty in designing controllers with good robust performance margins for EMWs operating at high rotor speeds is the highly vibratory nature of the flexible modes. The proximity of the poles and zeros of such plants to the imaginary axis imposes fundamental limitations on the achievable performance. This, together with the parameter-varying nature of the plant and the strict disturbance rejection specifications, makes ad-hoc or trial-and-error designs inadequate.

In research [14,23] we proposed a new hybrid scheme involving $\mathcal{H}_\infty$ loop-shaping and μ-synthesis to robustly control high-speed flexible flywheels supported on AMB's (Fig. 5). Performance

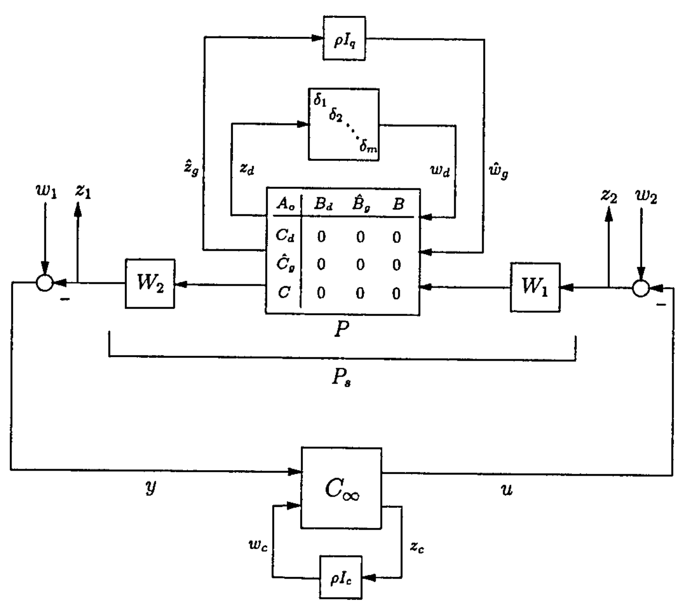

Figure 5: Block diagram for $\mathcal{H}_\infty$ loop-shaping framework. From [23].

requirements were specified through loop-shaping weights whereas robustness to parametric uncertainty was incorporated through a μ-synthesis design. In order to reduce the computational complexity of the control design and the order of the synthesized controllers, a method was devised to reduce the number of states that depend on the rotor speed. Numerical and experimental results demonstrated the effectiveness of the approach. See Fig. 6.

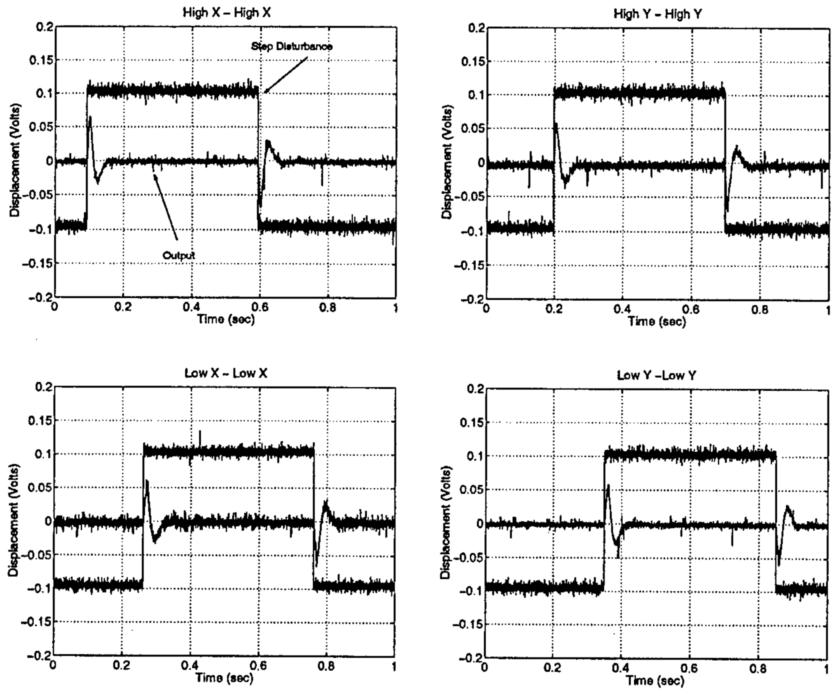

Figure 6: Disturbance rejection time response. From [23].

2.7 Stability Analysis of Parameter-Dependent LTI systems

Figure 7 shows a rotating flexible beam supported on a pair of bearings. It can be shown that

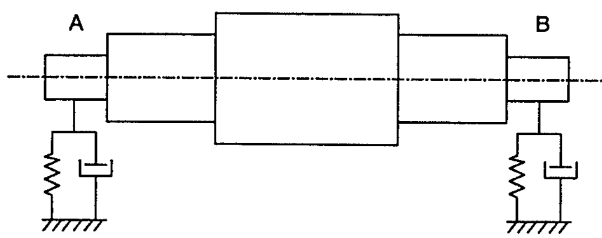

Figure 7: Simply supported flexible rotor beam.

the (uncontrolled) dynamics of the beam are described by the linear, time-invariant parameter-dependent (LTIPD) system of the form

$$\dot{x} = A(\rho)x = (A_0 + \rho A_1)x, \qquad \rho \in \Omega \tag{2}$$

In [13,19] we focused on deriving nonconservative stability conditions for (2). Specifically, in [13] the complete stability domain for LTIPD systems was synthesized by extending existing results in the literature. This domain is calculated through a guardian map which involves the determinant of the Kronecker sum of a matrix with itself. The stability domain in [13] can be synthesized for both single and multi-parameter dependent LTIPD systems. The determinant of the bialternate sum of a matrix with itself was also exploited in to reduce the computational complexity of the results.

Recall that for an LTI Parameter-Dependent (LTIPD) system of the form (2), stability can be established via the use of constant Lyapunov functions, say, of the form $V(x) = x^T P x$. When the parameter ρ varies in the set Ω or its value is not known a priori, a common (for all ρ) Lyapunov function can be used to check Hurwitz stability of the family of matrices $\{A(\rho), \rho \in \Omega\}$. The resulting notion of stability (quadratic stability) is nonetheless conservative, since the same Lyapunov matrix P is used for the whole parameter space. In order to achieve necessary and sufficient results one then needs to resort to the use of parameter-dependent Lyapunov functions of the form $V(x, \rho) = x^T P(\rho) x$. Since the explicit dependence of the Lyapunov matrix $P(\rho)$ on the parameter ρ is not known a priori, one typically postulates a convenient functional parameter dependence for $P(\rho)$, and then one proceeds to derive the stability conditions. This approach leads to conditions which are sufficient but not necessary. In order to obtain nonconservative (i.e., necessary and sufficient) conditions it is imperative to know the "correct" parameter dependence for the Lyapunov function. By "correct" we mean a Lyapunov function which depends on the parameter ρ in such a way, that for those values of the parameter for which the system is stable the stability conditions are satisfied, while for the values of the parameter for which the system is not stable, the stability conditions fail. In [19] we showed that for LTI systems depending on a single, constant parameter in an affine manner, nonconservative stability tests can be derived by restricting the search over Lyapunov matrices which depend *polynomially* on the parameter. Therefore, a polynomial-type Lyapunov matrix (of known degree) is suggested in [19], which can be used to derive necessary and sufficient stability conditions for single-parameter LTIPD systems. Moreover, it is shown that the conditions for checking the stability of an LTIPD system over a compact interval can be expressed into computable, non-conservative linear matrix inequalities (LMIs).

2.8 Low- and Zero-Bias Control of Active Magnetic Bearings

The force generated by an electromechanically activated bearing is a nonlinear function of the flux (or current). As a result, it is customary to linearize the force/flux characteristic by introducing a bias flux (or current). Typical values of the bias current are one-third to one-half of the maximum (saturation) current level for each electromagnet. Since electromagnetic losses at the bearings are proportional to the bias flux, operation with very small or zero bias is imperative for power efficiency. However, complete elimination of the bias flux results in a linearly uncontrollable system. Zero-bias operation thus calls for nonlinear control techniques. An additional complication arises from the fact that the AMB exhibits a deadzone-like characteristic with reduced force slew-rate capability at zero bias. Standard control designs for a zero-bias AMB result in a singularity manifesting itself as infinite voltage commands when the flux is zero.

In [3,15] we studied the stabilization problem of a zero-bias AMB using control Lyapunov functions. Specifically, we concentrated on alleviating or removing the singularity of zero-bias, voltage-controlled designs when the control flux is zero. This was done by applying a novel integrator-backstepping design for a special class of cascade systems. The proposed zero-bias control laws are either singularity-free or have a region of singularity that is much smaller than that of standard methods (i.e., using backstepping or feedback linearization). Furthermore, we improved upon current results in the literature by providing a singularity-free design using ideas from passivity theory. We showed the improved performance and design flexibility of the proposed designs via numerical simulations using a high-fidelity model. A crucial ingredient in the techniques of [3,15] is a novel voltage switching scheme that allows reduction of the bias current (or flux) while the AMB equations remain controllable. An experimental facility has also been constructed (shown in

Fig. 8) to test these low- and zero-bias control laws. The results of these experiments are reported in [26].

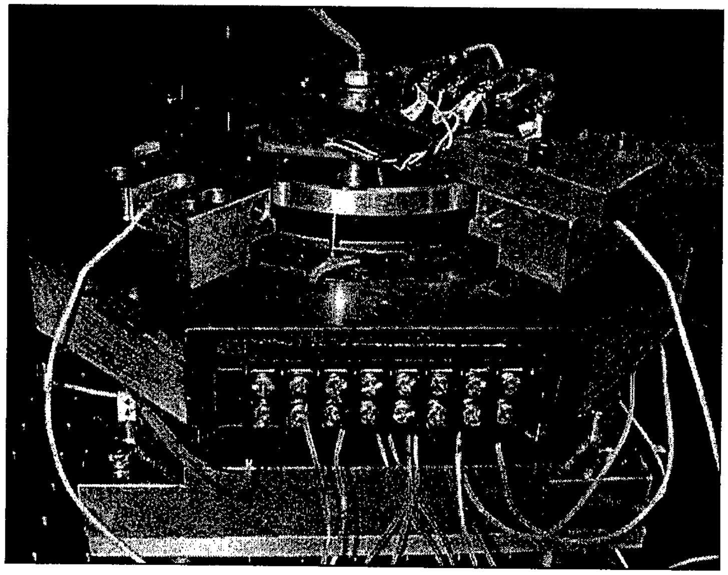

Figure 8: Experimental facility to test low- and zero-bias control laws for AMBs. From [26].

2.9 State- and Output-Feedback LB Control of ABMs

In addition to the zero-bias designs of [3,15], low-bias techniques [4,11,22] were also developed. Several stabilizing controllers were derived in [11,22] by applying recent results from nonlinear control theory. These results can be summarized as follows.

A simplified AMB model consisting of two identical electromagnets operated in voltage mode can be described by the simple equations (nondimensionalized form)

$$\dot{x}_1 = x_2, \qquad \dot{x}_2 = \varepsilon x_3 + x_3|x_3| := \varepsilon x_3 + \eta(x_3), \qquad \dot{x}_3 = \mathrm{sat}_\lambda(v)\,. \tag{3}$$

where ε denotes the bias level, which is considered to be very small $\varepsilon \ll 1$. The equations (3) result from the implementation of a novel flux-based voltage-switching scheme for voltage-controlled AMBs [3,15]. In (3) v is the (normalized) voltage command and λ is the (normalized) maximum voltage level.

Three different state-feedback designs have been proposed in [11,22]. The first design uses passivity ideas and results to the soft-saturated control law

$$v = -k_2x_2 - k_3x_3 - \mathrm{sat}_\lambda(\varepsilon^2\mathrm{sat}(k_1z) + \varepsilon x_3 + x_3|x_3|)\,, \quad k_1, k_2, k_3, \lambda > 0 \tag{4}$$

The second design uses the asymptotic small-gain theorem of Teel and leads to the soft-saturated control law

$$v = -k_2x_2 - k_3x_3 - \mathrm{sat}_\lambda\left(B^TPx\right) \tag{5}$$

The third state-feedback design uses nested saturation ideas of and is given by

$$v = -\mathrm{sat}_\lambda\left(kx_3 + \mathrm{sat}_{\lambda_1}\left(\frac{k^2}{\varepsilon}x_2 + kx_3 + \mathrm{sat}_{\lambda_2}\left(\frac{k^3}{\varepsilon}x_1 + \frac{2k^2}{\varepsilon}x_2 + kx_3\right)\right)\right) \tag{6}$$

with $0 < k, \quad 0 < \lambda, 0 < \lambda_1 < \min\{\lambda/2, k\varepsilon/5\}, 2\lambda_1^2/\varepsilon k < \lambda_2 < \lambda_1(1 - \lambda_1^\varepsilon k)/2$.

In practice, the flux measurement (x_3) needed in (4), (5) and (6) may not be feasible. A reduced order flux observer has thus been designed in [11,22] to estimate the flux. This observer is given by

$$\dot{\hat{\chi}} = v - \kappa\left(\hat{\chi} + \frac{\kappa}{\varepsilon}y\right) - \frac{\kappa}{\varepsilon}\eta(\hat{\chi} + \frac{\kappa}{\varepsilon}y), \qquad \hat{x}_3 = \hat{\chi} + \frac{\kappa}{\varepsilon}y, \tag{7}$$

where $\kappa > 0$ and where $\chi := x_3 - (\kappa/\varepsilon)y$ and $y = x_2$.

As shown in [11,22] this flux observer, when interconnected in a certainty-equivalence implementation with each of the previous three state-feedback controllers, results in a globally asymptotically stable system. This is a nontrivial result since, in general, the separation principle does not hold for general nonlinear systems and the stabilizability properties of a state feedback control law with the observer estimate can not be ensured a priori. Figure 9, for instance, shows state-feedback and output-feedback trajectories with the control (5).

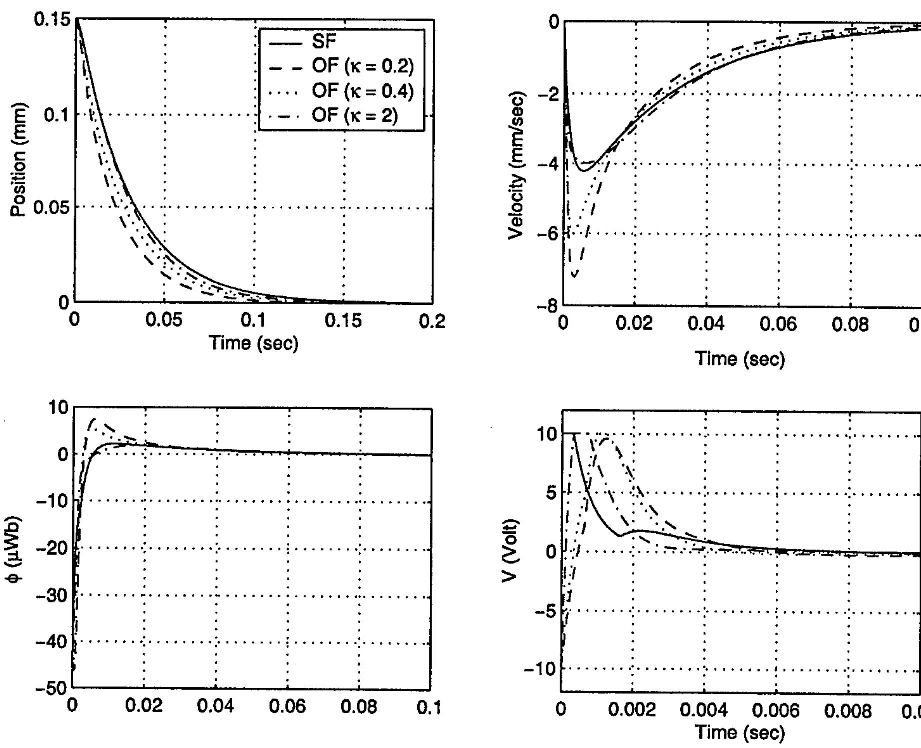

Figure 9: State-feedback and output-feedback system trajectories with control law (5) and different observer gains. Controller gains $k_2 = k_3 = 5$. From [22].

2.10 An Educational Spacecraft Simulator

A spacecraft simulator has been constructed at the School of Aerospace Engineering at the Georgia Institute of Technology to educate graduate and undergraduate students in the area of spacecraft attitude dynamics and control. A virtually torque-free environment is achieved by carefully balancing the spacecraft platform (the spacecraft "bus") on a hemi-spherical air bearing. The spacecraft bus is composed of a 24in diameter (0.75in thick) aluminum disk supported on the air bearing. The platform supports all the various spacecraft components, i.e., sensors, actuators, control computer, etc.; see Fig. 10.

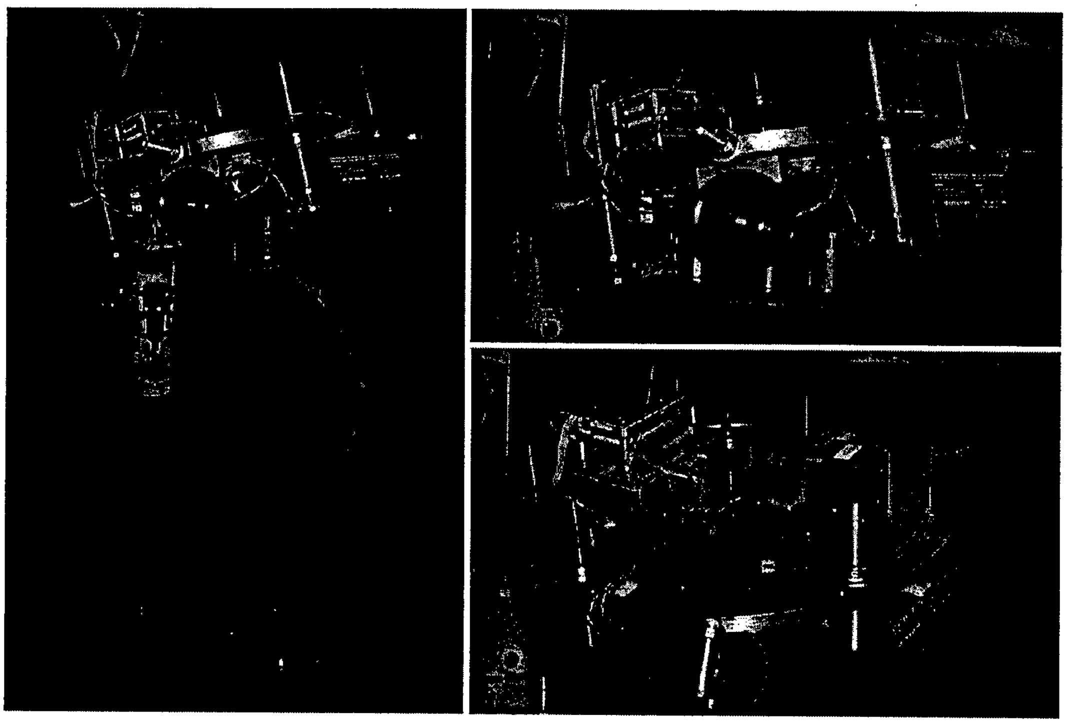

Figure 10: The Educational Spacecraft Simulator. From [20].

Several counterweights are used to balance the whole assembly so that its center of rotation coincides with its center of mass. The air-bearing is operated using compressed air through an air filter. In addition to removing moisture, oil and other impurities, the filter also regulates the air pressure (roughly around 25-40 psi depending on the normal load). At the moment, three momentum wheels are used as actuators. They are driven by three Maxon DC motors (Model 143683, with a stall torque of 780 mNm) connected to three Copley power amplifiers (Model 403). Encoders installed on the DC motors provide angular feedback. Power to the entire system is provided by six 12V batteries connected pairwise in series to provide 24V at a time. Angular position and rate information is provided by an Inertial Measurement Unit (DMU-AHRS by Crossbow, Inc.). All control tasks are run on the onboard computer (CMP5e). This is a PC104-type Pentium 266MHz main board computer. This board is used for the data acquisition, recording, controller implementation and communication. A remote PC and the CMP5e are connected via a wireless RS-232 serial port. The remote PC monitors the status of the experiments and issues start/stop commands, while the CMP5e unit controls the platform directly. More details on the design and construction of this facility, as well as the results from experimental testing of attitude control laws using this facility can be found in [10,20].

2.11 An Integrated Attitude Control Simulator for Research on Spacecraft Control

A second-generation spacecraft simulator (shown in Fig. 11) has been designed, constructed and installed at the basement of the Montgomery Knight building at the School of Aerospace Engineering at Georgia Tech. The funds for this high-fidelity experimental facility was provided by the AFOSR/DURIP award F49620-01-1-0198.

The principal component of the simulator is a cylindrical platform located on a hemi-spherical air bearing that allows friction-free rotation about three axes. The simulator includes a variety of actuators and sensors: gas thrusters, variable-speed controlled momentum gyros (VSCMGs) (which can operate solely in a reaction wheel (RW) or in a control momentum gyro (CMG) mode), a two-axial sun sensor, a high-precision three-axial rate gyro, a three-axial magnetometer, and a complementary inertial measurement unit. The facility offers a truly integrated attitude control system (IACS) for experimentally testing advanced attitude determination and control algorithms. The four VSCMGs, in particular, allow the validation of IPACS control laws.

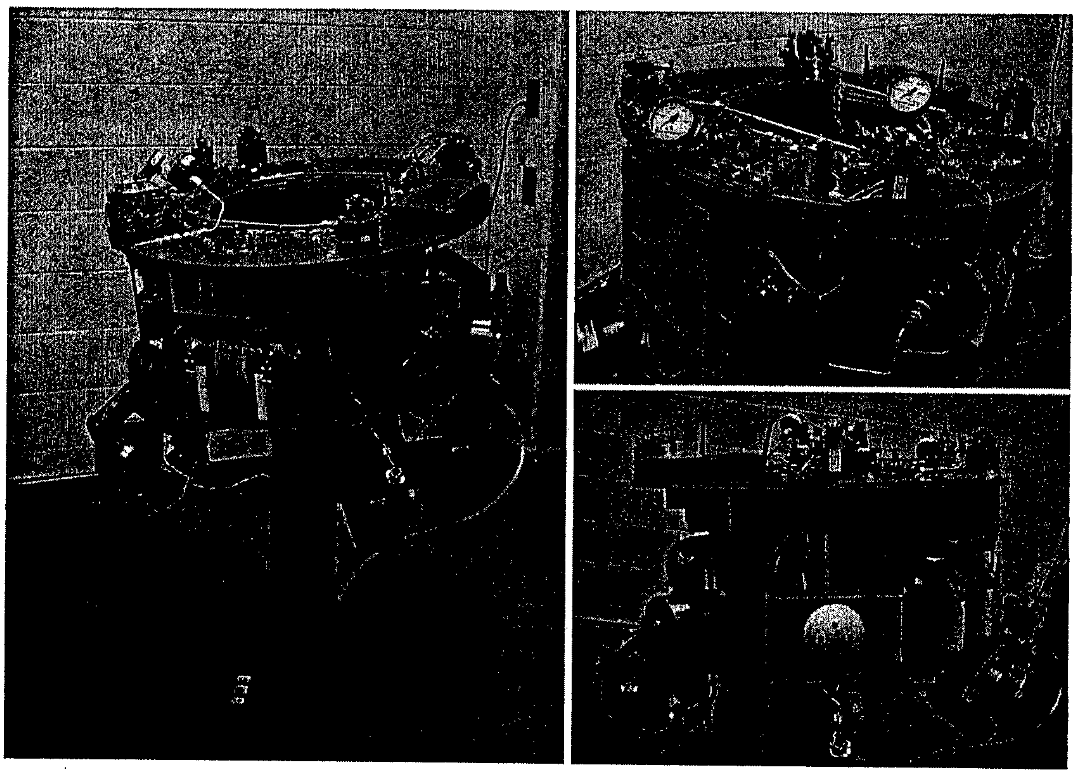

Figure 11: The completed IACS spacecraft simulator.

A recursive least squares algorithm has been developed and implemented to estimate the moment of inertia matrix and the location of the center of gravity. A nonlinear attitude control law was also been designed and turned on when excessive angular displacement of the platform is detected to avoid damaging the platform. A DC servo loop (PI with Smith predictor), shown in Fig. 12, was designed to command wheel speed acceleration in RW mode. The use of the Smith predictor was necessary owing to the significant time lags intrinsic in the sensor and actuator hardware. A separate internal servo-loop (implemented in hardware) deals with the gimbal rate commands in CMG

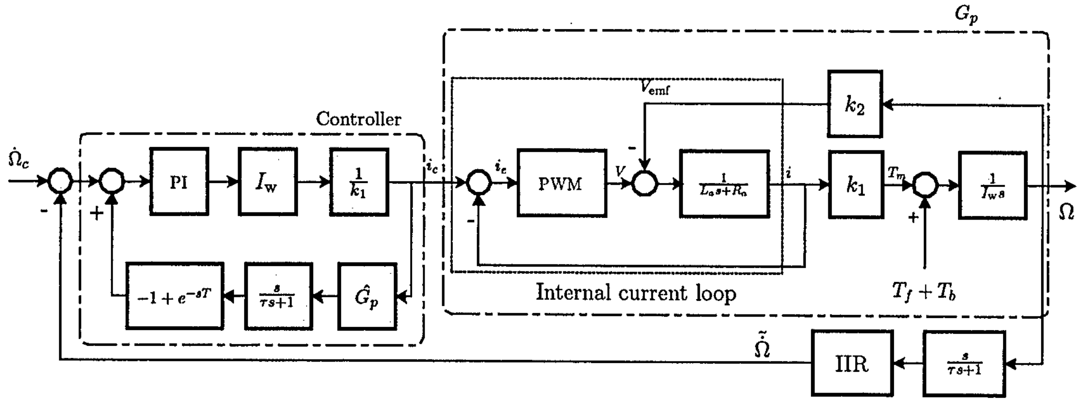

Figure 12: Implementation of PI servo loop with Smith predictor. From [18].

mode. Figure 13 compares experimental and simulation results for a simple stabilizing case. The results show very good correlation between experimental and simulated responses. Reference [18]

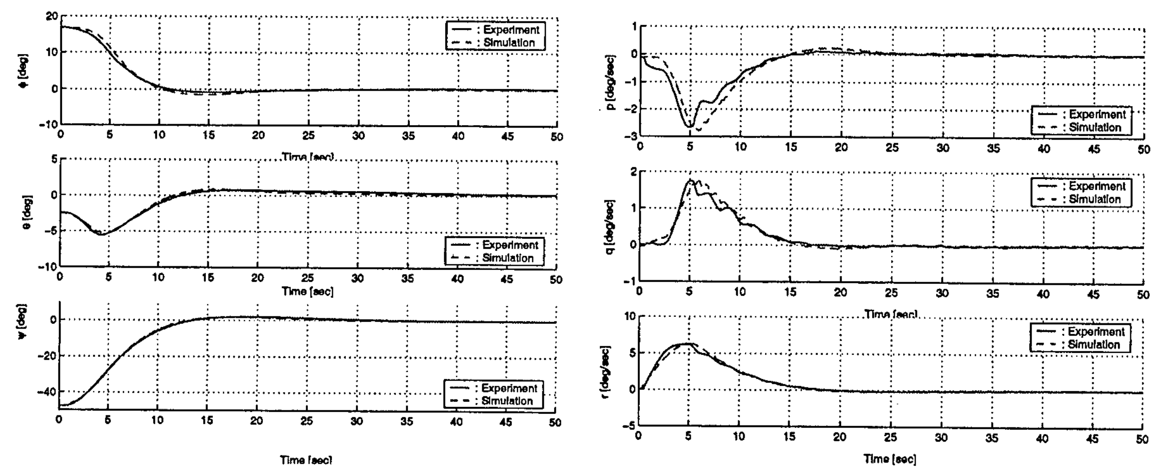

Figure 13: Comparison between simulation and experiment. Euler angles and rates. From [18].

gives a complete overview of the simulator specifications, along with the details for the design of the DC wheel servo loops.

3 Research Personnel Supported

Faculty

Prof. Panagiotis Tsiotras, Principal Investigator

Graduate Students

Brian Wilson, Ph.D.
Huyngjoo Yoon, Ph.D.
Dongwon Jung, Ph.D.

Viktoria Doumtchenko, M.S.
Ancil Marshall, M.S.
Kim ByungMoon, M.S.

In addition to the previous personnel, one post-doctoral student (Dr. Alex Lanzon) and four more graduate students (X. Zhang, E. Velenis, A. Schleicher and D. Richie) were also directly involved with this research program although their financial support did not come directly from this AFOSR award. An undergraduate student (P. Kriengsiri) assisted with the design and construction of the educational spacecraft simulator.

Two of the graduate students (D. Richie and B. Wilson) worked in the AFRL/VS during the summers of 2000 and 2001 via the Air Force Space Scholars Program.

4 Interactions and Transitions

4.1 Participation and Presentations

The following conferences and workshops were attended:

- *IEEE International Conference on Control Applications*, Ancorage, AK, Sept. 25-27, 2000.
- *Aerospace Flywheel Workshop*, AFRL, Albuquerque, NM, Oct. 17-18, 2000.
  AIAA Guidance, Navigation and Control Conference, Denver, Colorado, Aug. 14–17, 2000.
- *39th IEEE Conference on Decision and Control*, Sydney, Australia, Dec. 12-15, 2000.
- *American Control Conference*, Arlington, VA, June 25-27 , 2001.
- *AAS/AIAA Astrodynamics Conference*, Quebec City, Canada, July 30-August 2, 2001,
- *Digital Avionics Systems Conference*, Daytona Beach, Florida, October 14-18 , 2001.
- *Aerospace Flywheel Workshop*, Glenn Research Center, Cleveland, OH, March 14–15, 2002.
- *Proceedings, 41st IEEE Conference on Decision and Control*, Las Vegas, Nevada, December 10-13, 2002
- *10th Mediterranean Conference on Control and Automation (MED2002)*, Lisbon, Portugal
- *15th IFAC World Congress*, Barcelona, Spain, July 21-26, 2002.
- *Aerospace Flywheel Workshop*, Fort MacArthur, Los Angeles AFB, CA, August 6–8, 2003.
- *AIAA Guidance, Navigation and Control Conference*, Austin, TX, 2003.
- *42nd IEEE Conference on Decision and Control*, Maui, HW, December 9-12, 2003.

Furthermore, conference articles [1,2,3,4,6,7,9,10,11,13,14,17,18,19] were presented.

4.2 Transitions

The Air Force Research Lab in Albuquerque, NM has a program on Flywheel Attitude Control, Energy Transmission and Storage (FACETS). This program will combine all, or part, of the energy storage, attitude control, and power management and distribution (PMAD) subsystems into a single system, significantly decreasing bus mass (and volume) of future satellites. The Principal

Investigator established an Educational Partnership Agreement (EPA) between Georgia Tech and the Space Vehicle Directorate of the Air Force Research Lab (AFRL) at Kirkland AFB, in New Mexico to support the FACETS program. The objective of this EPA is the collaboration between GIT and AFRL for the development of new, nonlinear and adaptive control laws of spacecraft that can consolidate the operations of attitude control and energy storage. The technical monitor at AFRL is Dr. Jerry Fausz (505) 846-7890. The FACETS program at AFRL will validate IPACS control laws on the refurbished ASTREX facility. During the summer of 2000, Captain David Richie visited AFRL/VS under this EPA and the Space Scholars Program and worked on the integration of the ASTREX facility. During the summer of 2001, Brian Wilson visited AFRL/VS under this EPA and the Space Scholars Program. It is envisioned that the control laws developed at GIT will be transferred to AFRL, tested on the ASTREX facility, and be subsequently used in the future generation of Air Force satellites.

4.3 Patents

The following patents were the direct result of the research effort under this project:

- "Control of Magnetic Bearing-Supported Rotors", with R. Bartlett and P. Allaire, U.S. Patent No. 6,267,876 B1, (issued July 31, 2001).
- "Wheel-Equalization Algorithm for Simultaneous Attitude Control and Power Management of Satellites in Orbit Using Variable-Speed Control Moment Gyroscopes", with and H. Yoon, (pending).
- "Simultaneous Attitude Control and Power Management of Satellites in Orbit Using Variable-Speed Control Moment Gyroscopes", with H. Yoon, (pending).

5 Honors and Awards

- Re-Elected to the Editorial Board of *AIAA Journal of Guidance, Control and Dynamics*, 2000–
- Elected to the Editorial Board of *Dynamics and Control: An International Journal*, 2000–2002
- Elected to the Editorial Board of *IEEE Control Systems Magazine*, 2003–
- Elected *Associate Fellow* of the American Instituted of Aeronautics and Astronautics, 2002–
- Elected *Senior Member* of the Institute of Electrical and Electronics Engineers, 2002–

6 Acknowledgment/Disclaimer

This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grant/contract number F49620-00-1-0374 and the AFOSR/DURIP award number F49620-01-1-0198. The views and conclusions contained herein are those of the author and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

7 Research Publications and Presentations under this AFOSR Award

7.1 Doctoral Dissertations and Master's Theses

The following dissertations and theses directly of indirectly have benefited from the support of this AFOSR award.

1. "Control Design for Low-Loss Active Magnetic Bearings: Theory and Implementation," Ph.D. dissertation, (B. Wilson), School of Electrical and Computer Engineering, Georgia Institute of Technology, March 2004.
2. "Parameter-Dependent Lyapunov Functions and Stability Analysis of Linear Parameter-Dependent Dynamical Systems," Ph.D. dissertation, (X. Zhang), School of Aerospace Engineering, Georgia Institute of Technology, September 2003.
3. "Combined Attitude Control and Energy Storage Using VSCMG's," M.S. thesis, (D. Richie), School of Aerospace Engineering, Georgia Institute of Technology, May 2001.

7.2 Journal and Conference Publications

1. Fausz, J. and Richie, D., "Flywheel Simultaneous Attitude Control and Energy Storage using VSCMGs," *IEEE International Conference on Control Applications*, Ancorage, AK, pp. 991–995, Sept. 25–27, 2000.
2. Tsiotras, P., and Schleicher, A. "Partial Attitude Stabilization of a Rigid Spacecraft under Actuator Failure," AIAA Paper 00-4044, *AIAA Guidance, Navigation and Control Conference*, Denver, Colorado, Aug. 14–17, 2000.
3. Tsiotras, P., Wilson, B., and Bartlett, R. "Control of a Zero-Bias Magnetic Bearing Using Control Lyapunov Functions," *Proceedings, 39th IEEE Conference on Decision and Control*, Sydney, Australia, Dec. 12-15, pp. 4048–4053, 2000.
4. Tsiotras, P. and Velenis, E., "Low-Bias Control of AMB's Subject to Saturation Constraints," *IEEE International Conference on Control Applications*, Ancorage, Alaska, September 25-27, 2000, pp. 138–143
5. Tsiotras, P., Shen, H. and Hall, C., "Satellite Attitude Control and Power Tracking with Momentum Wheels," *AIAA Journal of Guidance, Control, and Dynamics* Vol. 24, No. 1, pp. 23-34, 2001.
6. Richie, D., Tsiotras, P. and Fausz, J., "Simultaneous Attitude Control and Energy Storage Using VSCMGs: Theory and Simulation," *American Control Conference*, Arlington, VA, June 25-27 , 2001.
7. Richie, D. and Tsiotras, P., "Variable Speed Control Moment Gyroscope Workbench: A New Simulation Tool for Tomorrow's Spacecraft," *Digital Avionics Systems Conference*, Daytona Beach, Florida, October 14-18 , 2001.
8. Tsiotras, P. and Doumtchenko, V., "Control of Spacecraft Subject to Actuator Failures: State-of-the-Art and Open Problems," *Journal of the Astronautical Sciences, Journal of the Astronautical Sciences*, Vol. 48, Nos. 2 and 3, pp. 337–358, 2001.

9. Yoon, H., and Tsiotras, P., "Spacecraft Attitude Control And Power Tracking with Single-Gimballed VSCMGs and Wheel Speed Equalization," AAS Paper 01-379, *AAS/AIAA Astrodynamics Conference*, Quebec City, Canada, July 30-August 2, 2001, pp. 1121–1138.

10. Kim, B., Velenis, E., Kriengsiri, P. and Tsiotras, P., "A Spacecraft Simulator for Research and Education," AAS Paper 01-367, *AAS/AIAA Astrodynamics Conference*, Quebec City, Canada, July 30–August 2, 2001, pp. 897–914.

11. Tsiotras, P. and Arcak, M., "Low-Bias Control of AMB Subject to Voltage Saturation: State-Feedback and Observer Designs," *Proceedings, 41st IEEE Conference on Decision and Control*, Las Vegas, Nevada, December 10-13, 2002, pp. 2474–2479.

12. Yoon, H. and Tsiotras, P. "Spacecraft Adaptive Attitude Control And Power Tracking With Single-Gimballed Variable Speed Control Moment Gyroscopes," *Journal of Guidance, Control, and Dynamics*, Vol. 25, No. 6, pp. 1081–1090, 2002.

13. Zhang, X., Lanzon, A. and Tsiotras, P., "On Robust Stability of LTI Parameter Dependent Systems ," *10th Mediterranean Conference on Control and Automation (MED2002)*, Lisbon, Portugal, July 9-12, 2002.

14. Lanzon, A. and Tsiotras, P., "Robust Control of Energy Momentum Wheels Supported on Active Magnetic Bearings using $\mathcal{H}_\infty$ Loop-Shaping and μ-Synthesis," *15th IFAC World Congress*, Barcelona, Spain, July 21-26, 2002.

15. Tsiotras, P. and Wilson, B.C., "Zero- and Low-Bias Control Designs for Active Magnetic Bearings," for *IEEE Transactions on Control Systems Technology*, Vol. 11, No. 6, pp. 889–904, 2003.

16. Hall, C., Tsiotras, P. and Shen, H., "Tracking Rigid Body Motion Using Thrusters and Momentum Wheels," *Journal of the Astronautical Sciences*, Vol. 50, No. 3, pp. 311–323, 2003.

17. Marshall, A. and Tsiotras P., "Spacecraft Angular Velocity Stabilization Using A Single-Gimbal Variable Speed Control Moment Gyro," AIAA Paper 03-5654, *AIAA Guidance, Navigation and Control Conference*, Austin, TX, 2003.

18. Jung, D. and Tsiotras, P., "A 3-DoF Experimental Test-Bed for Integrated Attitude Dynamics and Control Research," AIAA Paper 03-5331, *AIAA Guidance, Navigation and Control Conference*, , Austin, TX, 2003.

19. Zhang, X., Tsiotras, P. and Iwasaki, T., "Parameter-Dependent Lyapunov Functions for Stability Analysis of LTI Parameter Dependent Systems," *42nd IEEE Conference on Decision and Control*, Maui, HW, December 9-12, 2003.

20. Kim, B., Velenis, E., Kriengsiri, P. and Tsiotras, P., "A Low-Cost Spacecraft Simulator for Research and Education," *IEEE Control Systems Magazine*, Vol. 23, No. 3, pp. 26–37, 2003.

21. Yoon, H. and Tsiotras, P., "Singularity Analysis of Variable Speed Control Moment Gyros," *Journal of Guidance, Control, and Dynamics*, (to appear).

22. Tsiotras, P. and Arcak, M., "Low-Bias Control of AMB Subject to Voltage Saturation: State-Feedback and Observer Designs," *IEEE Transactions on Control Systems Technology*, (to appear).

23. Lanzon, A. and Tsiotras, P., "A Hybrid Combination of $\mathcal{H}_\infty$ Loop-Shaping and μ-Synthesis for Control of High Speed Flywheels," *IEEE Transactions of Control Systems Technology*, (under review; submitted February 2003).

24. Yoon, H. and Tsiotras, P., "Singularity Analysis and Avoidance for VSCMGs – Part I: No Power Constraint Case," *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, Providence, RI, August 16–19, 2004.

25. Yoon, H. and Tsiotras, P., "Singularity Analysis and Avoidance for VSCMGs – Part II: Power Constraint Case," *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, Providence, RI, August 16–19, 2004.

26. Wilson, C., Tsiotras, P. and Heck, B., "Experimental Validation of Zero- and Low-Bias Control Laws for AMB's," *AIAA Guidance, Navigation, and Control Conference*, Providence, RI, August 16–19, 2004.