Attitude Estimation And Control Of Manoeuvring Spacecraft

Fundamentals of Space Systems was developed to satisfy two objectives: the first is to provide a text suitable for use in an advanced undergraduate or beginning graduate course in both space systems engineering and space system design. The second is to be a primer and reference book for space professionals wishing to broaden their capabilities to develop, manage the development, or operate space systems. The authors of the individual chapters are practicing engineers that have had extensive experience in developing sophisticated experimental and operational spacecraft systems in addition to having experience teaching the subject material. The text presents the fundamentals of all the subsystems of a spacecraft missions and includes illustrative examples drawn from actual experience to enhance the learning experience. It includes a chapter on each of the relevant major disciplines and subsystems including space systems engineering, space environment, astrodynamics, propulsion and flight mechanics, attitude determination and control, power systems, thermal control, configuration management and structures, communications, command and telemetry, data processing, embedded flight software, survuvability and reliability, integration and test, mission operations, and the initial conceptual design of a typical small spacecraft mission.

This thesis investigates a new concept for the flexible design and verification of an ADCS for a nanosatellite platform. In order to investigate guidelines for the design of a flexible ADCS, observations of the satellite market and missions are recorded. Following these observations, the author formulates design criteria which serve as a reference for the conceptual design of the flexible ADCS. The research of the thesis was carried out during the development of TU Berlin's nanosatellite platform TUBiX20 and its first two missions, TechnoSat and TUBIN. TUBiX20 targets modularity, reuse and dependability as main design goals. Based on the analysis of design criteria for a flexible ADCS, these key design considerations for the TUBiX20 platform were continued for the investigations carried out in this thesis. The resulting concept implements the ADCS as a distributed system of devices complemented by a hardware-independent core application for state determination and control. Drawing on the technique of component-based software engineering, the system is partitioned into self-contained modules which implement unified interfaces. These interfaces specify the state quantity of an input or output but also its unit and coordinate system, complemented by a mathematical symbol for unambiguous documentation. The design and verification process for the TUBiX20 ADCS was also elaborated during the course of this research. The approach targets the gradual development of the subsystem from a purely virtual satellite within a closed-loop simulation to the verification of the fully integrated system on an air-bearing testbed. Finally, the concurrent realization of the investigated concept within the TechnoSat and TUBIN missions is discussed. Starting with the individual ADCS requirements, the scalability of the approach is demonstrated in three stages: from a coarse, but cost- and energy-efficient configuration to realize a technology demonstration mission with moderate requirements (TechnoSat) to a high-performance configuration to support Earth observation missions (TUBIN). Diese Dissertation untersucht ein neues Konzept zur flexiblen Entwicklung und Verifikation eines Lageregelungssystems f ü r eine Nanosatellitenplattform. Als Grundlage f ü r die Erarbeitung eines Leitfadens f ü r die Entwicklung werden zun ä chst Beobachtung des Satellitenmarkts sowie konkreter Missionen zusammengetragen. Darauf aufbauend formuliert der Autor Entwurfskriterien f ü r die Konzipierung eines flexiblen Lageregelungssystems. Die Dissertation wurde im Rahmen der Entwicklung der TUBiX20 Nanosatellitenplattform und ihrer ersten beiden Missionen, TechnoSat und TUBIN, an der TU Berlin durchgef ü hrt. TUBiX20 verfolgt Modularit ä t, Wiederverwendung und Zuverl ä ssigkeit als Entwicklungsziele. Diese werden unter der Verwendung der vom Autor hergeleiteten Entwurfskriterien in dieser Arbeit im Kontext des Lageregelungssystems verfeinert. Das resultierende Konzept setzt dieses als verteiltes System von Ger ä ten und einem hardware-unabh ä ngigen Software-Kern um. Der Software-Entwurfstechnik Component-based software engineering folgend ist das System in unabh ä ngige Module unterteilt, welche wiederum einheitliche Schnittstellen implementieren. Diese Schnittstellen spezifizieren die Zustandsgrößen für die Ein- und Ausgänge der Module inklusive Einheit, Koordinatensystem und mathematischem Symbol für eine eindeutige Darstellung. Der Entwurfs- und Verifikationsprozess für das TUBiX20 Lageregelungssystem wurde vom Autor im Rahmen der Arbeit untersucht. Hier verfolgt der Ansatz einen schrittweisen übergang von einem virtuellen Satelliten als Simulationsmodell bis hin zur Verifikation des integrierten Systems auf einem Lageregelungsteststand. Abschließend diskutiert die Arbeit die Realisierung des untersuchten Konzepts im Rahmen der Missionen TechnoSat und TUBIN. Beginnend mit den jeweiligen Anforderungen wird die Skalierbarkeit des Ansatzes in drei Stufen demonstriert: von einer groben, aber kosten- und energieeffizienten Konfiguration für eine Technologieerprobungsmission mit moderaten Anforderungen (TechnoSat) bis hin zu einer Konfiguration für hochgenaue Lageregelung als Basis für Erdbeobachtungsmissionen (TUBIN).

The paper presents an approach to on-board commanding, estimation, and control of the attitude motion of maneuvering spacecraft, based on modern control principles. Firstly the control algorithms are discussed. The control law is based on explicit model following. It comprises single-axis models of the spacecraft motion, which generate a target trajectory and associated target control. The spacecraft tracks the target trajectory by means of the target control which is fed forward to the spacecraft, and by means of state feedback control. A spacecraft state estimator provides for the estimates of the spacecraft state (attitude, angular velocity), and provides for the estimate of the disturbance torque which is used for disturbance torque compensation. Secondly an algorithm for inertial-optical attitude determination and estimation of gyro parameters (drift rate bias and scale factor error) is presented. The algorithms were validated in software simulations of an attitude control system of the type as used in the Infra Red Astronomical Satellite (IRAS). The control law and state estimator were tested inflight, in an on-board experiment with the IRAS spacecraft. The considered control system comprises a strapdown rate-integrating gyro and a slit-type star sensor for optical-inertial attitude sensing, a reaction wheel actuator, and a 16-bit on-board computer. The estimation and control algorithms are described, design trade-offs are discussed, simulation results and in-flight results are presented. (Author).

Attitude estimation and control of earth-pointing satellites

Spacecraft Modeling, Attitude Determination, and Control

Attitude Stabilization for CubeSat

Fundamental Concepts and Applications

In-flight Attitude Estimation and Control Experiments with IRAS Based on Modern Control Theory

Satellites are used increasingly in telecommunications, scientific research, surveillance, and meteorology, and these satellites rely heavily on the effectiveness of complex onboard control systems. This 1997 book explains the basic theory of spacecraft dynamics and control and the practical aspects of controlling a satellite. The emphasis throughout is on analyzing and solving real-world engineering problems. For example, the author discusses orbital and rotational dynamics of spacecraft under a variety of environmental conditions, along with the realistic constraints imposed by available hardware. Among the topics covered are orbital dynamics, attitude dynamics, gravity gradient stabilization, single and dual spin stabilization, attitude maneuvers, attitude stabilization, and structural dynamics and liquid sloshing.

There has been an increasing interest in multi-disciplinary research on multisensor attitude estimation technology driven by its versatility and diverse areas of application, such as sensor networks, robotics, navigation, video, biomedicine, etc. Attitude estimation consists of the determination of rigid bodies' orientation in 3D space. This research area is a multilevel, multifaceted process handling the automatic association, correlation, estimation, and combination of data and information from several sources. Data fusion for attitude estimation is motivated by several issues and problems, such as data imperfection, data multi-modality, data dimensionality, processing framework, etc. While many of these problems have been identified and heavily investigated, no single data fusion algorithm is capable of addressing all the aforementioned challenges. The variety of methods in the literature focus on a subset of these issues to solve, which would be determined based on the application in hand. Historically, the problem of attitude estimation has been introduced by Grace Wahba in 1965 within the estimate of satellite attitude and aerospace applications. This book intends to provide the reader with both a generic and comprehensive view of contemporary data fusion methodologies for attitude estimation, as well as the most recent researches and novel advances on multisensor attitude estimation task. It explores the design of algorithms and architectures, benefits, and challenging aspects, as well as a broad array of disciplines, including: navigation, robotics, biomedicine, motion analysis, etc. A number of issues that make data fusion for attitude estimation a challenging task, and which will be discussed through the different chapters of the book, are related to: 1) The nature of sensors and information sources (accelerometer, gyroscope, magnetometer, GPS, inclinometer, etc.); 2) The computational ability at the sensors; 3) The theoretical developments and convergence proofs; 4) The system architecture, computational resources, fusion level.

Fundamentals of Spacecraft Attitude Determination and ControlSpringer

Attitude Estimation and Control of Earth-pointing Satellites

Quaternion-Based Approach

Attitude Estimation and Control of Earth-pointing Stallites

Attitude Control and Estimation

Automatic Control in Space

This book explores CubeSat technology, and develops a nonlinear mathematical model of a spacecraft with the assumption that the satellite is a rigid body. It places emphasis on the CubeSat subsystem, orbit dynamics and perturbations, the satellite attitude dynamic and modeling, and components of attitude determination and the control subsystem. The book focuses on the attitude stabilization methods of spacecraft, and presents gravity gradient stabilization,

aerodynamic stabilization, and permanent magnets stabilization as passive stabilization methods, and spin stabilization and three axis stabilization as active stabilization methods. It also discusses the need to develop a control system design, and describes the design of three controller configurations, namely the Proportional-Integral-Derivative Controller (PID), the Linear Quadratic Regulator (LQR), and the Fuzzy Logic Controller (FLC) and how they can be used to design the attitude control of CubeSat three-axis stabilization. Furthermore, it presents the design of a suitable attitude stabilization system by combining gravity gradient stabilization with magnetic torquing, and the design of magnetic coils which can be added in order to improve the accuracy of attitude stabilization. The book then investigates, simulates, and compares possible controller configurations that can be used to control the currents of magnetic coils when magnetic coils behave as the actuator of the system.

The attitude control problem, or the control of a spacecraft's orientation with respect to a frame of reference, is a challenging problem in space missions and has attracted much attention as it involves highly nonlinear characteristics of the governing equations. The attitude control task requires an estimation algorithm that deduces the attitude from strapdown sensor inputs and a control

algorithm that computes the necessary torques so that the vehicle can follow a desired attitude. From the perspective of control, feedback control laws are sought for the purpose of asymptotic trajectory tracking, with the ability to reject unexpected external disturbances, and be insensitive to parameter variations. An adaptive sliding mode spacecraft attitude controller that fulfills those requirements is discussed in this dissertation. Unit quaternions and Rodrigues parameters are used to parameterize attitude. Lyapunov stability theory is used to prove the stability of the closed-loop system. For attitude estimation with increased accuracy, strap-down gyroscopes and vector measurements are fused together. Because of the nonlinear nature of the attitude kinematics equation and the measurement model, the problem becomes a nonlinear state estimation problem, which is typically tackled by Bayesian inference. In this dissertation we discuss a marginalized particle filtering algorithm, to possibly increase the estimation accuracy and reduce the computation load compared with other non-parametric methods. We exploit the linear-substructure and further show that the linear state evolution is completely independent of the nonlinear partition. We have also investigated a computationally efficient and easy-to-tune sensor fusion algorithm, based on the complementary filter and the TRIAD algorithm. It is beneficial to use a complementary filter because rate

and angle sensor possess benefits and drawbacks in different frequency regimes. The proposed algorithm shows comparable performance to the EKF but with less computational burden. It aims to be implementable on a small portable platform. In applications of mobile robots, the cutoff frequency can be adapted based on a fuzzy logic in real-time to adjust trust to different sensors, to cope with problems such as motion accelerations and magnetic distortions.

One crucial part in achieving this task is the requirement of accurate knowledge of the system's attitude. To obtain information related to the systems attitude, a number of inertial sensors can be used. These sensors usually consist of accelerometers, magnetometers, and gyroscopes. All of these sensors are often used since each sensor has its own limitations. A description of the system aerodynamics is given to describe the system forces and torques.

Inertial-Optical Attitude Determination and Model Following Control of Manoeuvring Spacecraft

An Attitude Determination and Control System for the Cornell Nanosatellite

Fundamentals of Spacecraft Attitude Determination and Control

Optimal Estimation of Dynamic Systems

Attitude Estimation and Control of Manoeuvring Spacecraft

Most newcomers to the field of linear stochastic estimation go through a difficult process in understanding and applying the theory.This book minimizes the process while introducing the fundamentals of optimal estimation. Optimal Estimation of Dynamic Systems explores topics that are important in the field of control where the signals received are used to determine highly sensitive processes such as the flight path of a plane, the orbit of a space vehicle, or the control of a machine. The authors use dynamic models from mechanical and aerospace engineering to provide immediate results of estimation concepts with a minimal reliance on mathematical skills. The book documents the development of the central concepts and methods of optimal estimation theory in a manner accessible to engineering students, applied mathematicians, and practicing engineers. It includes rigorous theoretial derivations and a significant amount of qualitiative discussion and judgements. It also presents prototype algorithms, giving detail and discussion to stimulate development of efficient computer programs and intelligent use of them. This book illustrates the application of optimal estimation methods to problems with varying degrees of analytical and numercial difficulty. It compares various approaches to help develop a feel for the absolute and relative utility of different methods, and provides many applications in the fields of aerospace, mechanical, and electrical engineering.

First published in 2001. The classical Fourier transform is one of the most widely used mathematical tools in engineering. However, few engineers know that extensions of harmonic analysis to functions on groups holds great potential for solving problems in robotics, image analysis, mechanics, and other areas. For those that may be aware of its potential value, there is still no place they can turn to for a clear presentation of the background they need to apply the concept to engineering problems. Engineering Applications of Noncommutative Harmonic Analysis brings this powerful tool to the engineering world. Written specifically for engineers and computer scientists, it offers a practical treatment of harmonic analysis in the context of particular

Lie groups (rotation and Euclidean motion). It presents only a limited number of proofs, focusing instead on providing a review of the fundamental mathematical results unknown to most engineers and detailed discussions of specific applications. Advances in pure mathematics can lead to very tangible advances in engineering, but only if they are available and accessible to engineers. Engineering Applications of Noncommutative Harmonic Analysis provides the means for adding this valuable and effective technique to the engineer's toolbox.

This book features the latest theoretical results and techniques in the field of guidance, navigation, and control (GNC) of vehicles and aircraft. It covers a range of topics, including, but not limited to, intelligent computing communication and control; new methods of navigation, estimation, and tracking; control of multiple moving objects; manned and autonomous unmanned systems; guidance, navigation, and control of miniature aircraft; and sensor systems for guidance, navigation, and control. Presenting recent advances in the form of illustrations, tables, and text, it also provides detailed information of a number of the studies, to offer readers insights for their own research. In addition, the book addresses fundamental concepts and studies in the development of GNC, making it a valuable resource for both beginners and researchers wanting to further their understanding of guidance, navigation, and control.

NASA Technical Paper

High-precision Pointing and Attitude Estimation and Control Algorithms for Hardware-constrained Spacecraft

Advances in Guidance, Navigation and Control

mit 55 Literaturstellen

A flexible attitude control system for three-axis stabilized nanosatellites

This book explores topics that are central to the field of spacecraft attitude determination and control. The authors provide rigorous theoretical derivations of significant algorithms accompanied by a generous amount of qualitative discussions of the subject matter. The book documents the development of the important concepts and methods in a manner accessible to

practicing engineers, graduate-level engineering students and applied mathematicians. It includes detailed examples from actual mission designs to help ease the transition from theory to practice and also provides prototype algorithms that are readily available on the author ' s website. Subject matter includes both theoretical derivations and practical implementation of spacecraft attitude determination and control systems. It provides detailed derivations for attitude kinematics and dynamics and provides detailed description of the most widely used attitude parameterization, the quaternion. This title also provides a thorough treatise of attitude dynamics including Jacobian elliptical functions. It is the first known book to provide detailed derivations and explanations of state attitude determination and gives readers real-world examples from actual working spacecraft missions. The subject matter is chosen to fill the void of existing textbooks and treatises, especially in state and dynamics attitude determination. MATLAB code of all examples will be provided through an external website.
Small satellites use commercial off-the-shelf sensors and actuators for attitude determination and control (ADC) to reduce the cost. These sensors and actuators are usually not as robust as the available, more expensive, space-proven equipment. As a result, the ADC system of small satellites is more vulnerable to any fault compared to a system for larger competitors. This book aims to present useful solutions for fault tolerance in ADC systems of small satellites. The contents of the book can be divided into two categories: fault tolerant attitude filtering algorithms for small satellites and sensor calibration methods to compensate the sensor errors. MATLAB® will be used to demonstrate simulations. Presents fault tolerant attitude estimation algorithms for small satellites with an emphasis on algorithms ' practicability and applicability Incorporates fundamental knowledge about the attitude determination

methods at large Discusses comprehensive information about attitude sensors for small satellites Reviews calibration algorithms for small satellite magnetometers with simulated examples Supports theory with MATLAB simulation results which can be easily understood by individuals without a comprehensive background in this field Covers up-to-date discussions for small satellite attitude systems design Dr. Chingiz Hajiyev is a professor at the Faculty of Aeronautics and Astronautics, Istanbul Technical University (Istanbul, Turkey). Dr. Halil Ersin Soken is an assistant professor at the Aerospace Engineering Department, Middle East Technical University (Ankara, Turkey).

Automatic Control in Space is a compendium of papers presented on the Eighth IFAC Symposium that took place in Oxford, England in July 1979. The book is comprised of an assortment of presentations prepared by experts in the fields of engineering, computer science, robotics, optics, aeronautics, and other allied disciplines discussing various aspects and types of automatic control systems and applications used in space technology. The text covers a broad range of topics on space technology, such as stabilization systems for space telescopes and balloon platforms; spacecraft attitude estimation and space navigation; and various control algorithms for different motion stabilization problems. Robotic systems; automatic control for large space transportations; and a path selection system for an autonomous Martian roving vehicle are presented as well. The text will be of high interest for engineers, computer scientists, physicists, inventors, astronomers, and various experts in space technology.

Design and Implementation of an Attitude Estimation System to Control Orthopedic Components

Attitude Estimation, Modelling, and Control of Autonomous Underwater Vehicle
Flight Mechanics Symposium
Development of Novel Satellite Attitude Determination and Control Algorithms Based on Telemetry Data from an Earth Satellite
State Estimation for Robotics

A modern look at state estimation, targeted at students and practitioners of robotics, with emphasis on three-dimensional applications.

Roger D. Werking Head, Attitude Determination and Control Section National Aeronautics and Space Administration/ Goddard Space Flight Center Extensiye work has been done for many years in the areas of attitude determination, attitude prediction, and attitude control. During this time, it has been difficult to obtain reference material that provided a comprehensive overview of attitude support activities. This lack of reference material has made it difficult for those not intimately involved in attitude functions to become acquainted with the ideas and activities which are essential to understanding the various aspects of spacecraft attitude support. As a result, I felt the need for a document which could be used by a variety of persons to obtain an understanding of the work which has

been done in support of spacecraft attitude objectives. It is believed that this book, prepared by the Computer Sciences Corporation under the able direction of Dr. James Wertz, provides this type of reference. This book can serve as a reference for individuals involved in mission planning, attitude determination, and attitude dynamics; an introductory textbook for stu dents and professionals starting in this field; an information source for experimen ters or others involved in spacecraft-related work who need information on spacecraft orientation and how it is determined, but who have neither the time nor the resources to pursue the varied literature on this subject; and a tool for encouraging those who could expand this discipline to do so, because much remains to be done to satisfy future needs.

CubeSats are a specific subset of nanosatellites, and their common form factor and canisterized deployers have made it possible to undertake higher risk, lower cost missions that can supplement the current generation of large, monolithic, expensive satellites. Our objective in this thesis is to improve attitude estimation on CubeSats using Unscented Kalman filters. CubeSats have evolved from their relatively low complexity and low computational power beginnings.

This progression motivates us to revisit attitude determination estimation approaches commonly used for CubeSats, and to implement an alternative Kalman filtering method. Our goal is to improve the current state of the art in attitude estimation on previous MIT Space Systems Laboratory CubeSats by at least two orders of magnitude from about 1-5* attitude knowledge error down to 0.050 or better. This improvement benefits applications that require precise pointing, such as imaging and active tracking of specific targets, laser communications, and coordinated activity and observations among multiple CubeSats. We were able to achieve better than our pointing error goal of 0.05', and found that the proposed Unscented Kalman filter performed significantly better at high angular rate estimation than the Extended Kalman filter (already implemented on some CubeSats). The quaternion estimates were converted to Euler angles to improve ease of interpretation. For the majority of the missions, the mean total Euler angle estimation error improvement ranged from 83% - 98% with error variance decreased by as much as 98%. One implementation had more than a two order of magnitude improvement, to achieve 0.01* mean error, better than the desired pointing accuracy. We present a

detailed assessment of these estimation errors, along with changes in quaternion error that accompany varying the unscented filter parameters.

Improving Attitude Determination and Control of Resource-constrained CubeSats Using Unscented Kalman Filtering
Flight Mechanics Symposium 1997
Attitude Estimation and Control of a Ducted Fan VTOL UAV
Spacecraft Attitude Dynamics
With Emphasis on Rotation and Motion Groups

Space Microsystems and Micro/Nano Satellites covers the various reasoning and diverse applications of small satellites in both technical and regulatory aspects, also exploring the technical and operational innovations that are being introduced in the field. The Space Microsystem developed by the author is systematically introduced in this book, providing information on such topics as MEMS micro-magnetometers, MIMUs (Micro-inertia-measurement unit), micro-sun sensors, micro-star sensors, micro-propellers, micro-relays, etc. The book also examines the new technical standards, removal techniques or other methods that might help to address current problems, regulatory issues and procedures to ameliorate problems associated with small satellites, especially mounting levels of orbital debris and noncompliance with radio frequency and national licensing requirements, liabilities and export controls, Summarizing the scientific research experiences of the author and his team, this book holds a high scientific reference value as it gives readers comprehensive and thorough introductions to the micro/nano satellite and space applications of MEMS technology. Covers various reasoning and diverse applications for small satellites in both technical and regulatory aspects Represents the first publication that systematically introduces the Space Microsystem developed by the author Examines new technical standards, removal techniques and other methods that might help to address current problems, regulatory issues and procedures

This book discusses all spacecraft attitude control-related topics: spacecraft (including attitude measurements, actuator, and disturbance torques), modeling, spacecraft attitude determination and estimation, and spacecraft attitude controls. Unlike other books addressing these topics, this book focuses on quaternion-based methods because of its many merits. The book lays a brief, but necessary background on rotation sequence representations and frequently used reference frames that form the foundation of spacecraft attitude description. It then discusses the fundamentals of attitude determination using vector measurements, various efficient (including very recently developed) attitude determination algorithms, and the instruments and methods of popular vector measurements. With available attitude measurements, attitude control designs for inertial point and nadir pointing are presented in terms of required torques which are independent of actuators in use. Given the required control torques, some actuators are not able to generate the accurate control torques, therefore, spacecraft attitude control design methods with achievable torques for these actuators (for example, magnetic torque bars and control moment gyros) are provided. Some rigorous controllability results are provided. The book also includes attitude control in some special maneuvers, such as orbital-raising, docking and rendezvous, that are normally not discussed in similar books. Almost all design methods are based on state-spaced modern control approaches, such as linear quadratic optimal control, robust pole assignment control, model predictive control, and gain scheduling control. Applications of these methods to spacecraft attitude control problems are provided. Appendices are provided for readers who are not familiar with these topics.

Comprehensive coverage includes environmental torques, energy dissipation, motion equations for four archetypical systems, orientation parameters, illustrations of key concepts with on-orbit flight data, and typical engineering hardware. 1986 edition.

Spacecraft Dynamics and Control

Comprehensive Computer Simulation and Tradeoff Analysis for Precision Spacecraft Attitude Estimation and Control

Proceedings of 2020 International Conference on Guidance, Navigation and Control, ICGNC 2020, Tianjin, China, October 23–25, 2020

A Nonlinear Estimator for Reconstructing the Angular Velocity of a Spacecraft Without Rate Gyros

This 1997 book explains basic theory of spacecraft dynamics and control and the practical aspects of controlling a satellite.

The overarching objective of this thesis is to develop algorithms for high-precision pointing and attitude estimation and control on hardware-constrained spacecraft. This includes small spacecraft, where tight mass, volume, power, and cost constraints exist, as well as spacecraft where certain hardware has failed. As a case study, the attitude determination and control subsystem (ADCS) for ExoplanetSat will be designed.

ExoplanetSat is a three-unit CubeSat (10 x 10 x 34 cm, ~ 4 kg) designed to detect exoplanets around bright Sun-like stars via the transit method. To achieve the photometric precision necessary to detect Earth-sized exoplanets, a pointing precision on the arcsecond level must be achieved. This is an unprecedented level of pointing precision on a spacecraft of this size that will be accomplished through a two-stage control system: reaction wheels for coarse attitude control and a piezo stage for fine pointing control. A linear analysis developed using stochastic linearization techniques is used to analyze the various contributions to pointing error, allowing software improvements to be made, which decrease pointing error by as much as 50%. Simulations show that a pointing precision of 2.3 arcsec (3[sigma]) can be achieved, which is two to four orders of magnitude beyond the current capability of other comparable spacecraft. In addition to performing high-precision pointing, the spacecraft must perform many other ADCS modes. These modes are complicated due to the lack of certain hardware, specifically gyros and coarse Sun sensors covering the entire sky. To deturrble the spacecraft after initial deployment, a novel control algorithm is proposed that will simultaneously detumuble the spacecraft while avoiding angular rate observability singularities, allowing the rate to be properly estimated with a magnetometer alone throughout the detumnbling process. This is done by regulating the amount of kinetic energy in the system relative to the decreasing momentum, which

excites nutation in the spacecraft and maintains a full-rank nonlinear observability matrix. To search for the Sun, a guidance and control law is developed that efficiently searches the sky while navigating based on the body magnetic field direction alone and again avoiding observability singularities. During the slews between orbit day and night, the star camera is the main sensor. To dramatically reduce the image processing time, a method of tracking stars with small windows will be developed. To support this star camera mode, a new and efficient window generation technique is developed to find new stars to track as stars fall out of the field of view of the star camera during the slew. While these algorithms will be designed with ExoplanetSat in mind, they can easily be applied to other spacecraft with similar hardware. Finally, a three-degree-of-freedom air bearing testbed was developed to test some of these algorithms on flight-equivalent hardware in a representative environment. Testbed results show the ability to initialize the star camera and operate it in a fast windowed mode, use the reaction wheels to slew to a target attitude, and achieve 12 arcsec (3[sigma]) pointing with the reaction wheels and piezo stage. The simulation, modified to match the environment and parameters of the testbed, correctly predicted the testbed results within 10%, verifying the simulation and increasing confidence in the on-orbit simulation predictions. This successful hardware demonstration increases the technology readiness level (TRL) of this pointing control system to TRL 6.

Fundamentals of Space Systems
A Practical Engineering Approach
Proceedings of a Conference Sponsored by NASA Goddard Space Flight Center at Goddard Space Flight Center, Greenbelt, Maryland, May 19-21, 1997
Proceedings of the 8th IFAC Symposium, Oxford, England, 2-6 July 1979
Spacecraft Attitude Determination and Control