THE JER-NAN JUANG ASTRODYNAMICS SYMPOSIUM

Edited by
Manoranjan Majji
John L. Junkins

Volume 147

ADVANCES IN THE ASTRONAUTICAL SCIENCES

THE JER-NAN JUANG ASTRODYNAMICS SYMPOSIUM

EDITORS
Dr. Manoranjan Majji — University at Buffalo, The State University of New York
Dr. John L. Junkins — Texas A&M University

SERIES EDITOR
Robert H. Jacobs — Univelt, Incorporated

Front Cover Illustration:

Juang's System Identification Class made by Andy Hung and a figurine designed by Cheyenne Chen:

The cover illustration was made by Mr. Andy Hung who was Prof. Juang's graduate student of the Department of Engineering Science, National Cheng Kung University of Taiwan. He had studied dynamics of a spinning membrane under the guidance of Drs. Lucas Horta and Keats Wilkie at NASA/LaRC for one year. Andy presented his research results at the Jer-Nan Juang Astrodynamics Symposium. He was impressed by the participants' comments on Prof. Juang's achievements and came up an idea to make the cover illustration to describe his impression of taking Prof. Juang's class on system identification.

The superman figurine was a gift during a celebration of Juang's birthday. It expressed appreciation for raising more than US$100 millions for a five-year research funding to establish the Taiwan Advanced Research and Education Network (TWAREN) and a smart grid center.

THE JER-NAN JUANG ASTRODYNAMICS SYMPOSIUM

Volume 147
ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Manoranjan Majji
John L. Junkins

Proceedings of the AAS Jer-Nan Juang Astrodynamics Symposium held June 24–26, 2012, College Station, Texas.

Published for the American Astronautical Society by
Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 2013

Library of Congress Card No. 57-43769

ISSN 0065-3438

ISBN 978-0-87703-595-4 (Hard Cover Plus CD ROM)
ISBN 978-0-87703-596-1 (CD ROM)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

Printed and Bound in the U.S.A.

FOREWORD

It is the greatest honor that friends and colleagues would organize a technical symposium to celebrate and acknowledge one's contribution and life's work. This symposium was initiated by Prof. John Junkins and cosponsored by Texas A&M University and the American Astronautical Society (AAS). Due to the overwhelming response many more abstracts were received than could be accommodated in the manner originally planned (full papers presented, no parallel sessions). Accordingly, there were two presentation modes: session keynote paper presentations and interactive paper presentations. The presentations and papers were universally excellent, mainly covering the solution of inverse problems in dynamical systems broadly. Many new concepts were introduced for system identification, attitude determination and control, and system modeling for future space missions such as solar sail propulsion of spacecraft.

In the lunch keynote, Richard began introducing my early days by showing a soccer-team photo provided by my undergraduate classmate, Prof. Wen Chan of the University of Texas at Arlington. Then, he showed photos to give a brief introduction of our early collaboration in organizing an international symposium co-sponsored by National Cheng-Kung University (NCKU) and AAS in 1981. It was the first international conference ever held at NCKU, where I received my BS degree. A photo given by Lucas Horta showed a scale model of space station that we worked on in the mid-1980s. Jan Wright and Jonathan provided a photo showing my visit at Queen Mary College and Cambridge University. Kirsten Morris sent a message reminiscing about our time working together on an energy-based controller design for structures at NASA Langley — I taught a multi-day short course on control of flexible structures in her workshop at the Fields Institute of Waterloo in 1993.

Elouise and John Junkins put up a wonderful dinner party in their beautiful house for all the presenters and attendees. It was indeed an unforgettable party featuring a luscious garden, delicious homemade dishes, and blues music (my favorite) played by two musicians/guitarists; Mark Balas and Clifford Fry, who is a neighbor of John. It was a dream-like environment with old folks and young friends sitting around the garden to share our past histories and new ideas, and later enjoying blues in the house. John certainly established a new model of dinner party for other similar symposiums to follow!

The symposium ended with the most memorable banquet I have ever had in my life. John Junkins presented a slide show entitled "How to Live" giving several items of "unauthorized" quotations: "Cultivate a smile that will brighten not only your path, but the path of all around you"; "Choose interesting problems, set ambitious goals and never, ever, think about giving up"; "Make the boundary between work and play fuzzy"; "Half the fun of engineering is watching the light in the eyes of young colleagues when they get it"; "The other half of the fun is watching young people take ideas further than you thought possible"; "Basic research and applied research can do much better than peacefully co-exist", and "Flirt with a pretty girl, frequently." John has done better than me on all quotations except "maybe" the last one. I have been fortunate to be married for 35 years to a very pretty girl — my wonderful wife, Lily — but have not flirted with her frequently enough. John expressed his sympathy and apologies to Lily, and made an unambiguous conclusion that I need to write a new book entitled "How to Live". John and I have never co-authored a book and this is a good chance for us. John also showed a photo of our "Lecture Tour" of Taiwan, Japan, Hong Kong, and China in 1986. Lecturers were John Junkins, Daniel Inman, Robert Reiss, and myself. Terry Alfriend sent me a book that captures some of Hawaii's great beauty. Manoranjan Majji presented me with a calendar that describes Buffalo history. Richard Longman, Minh Phan, Landis Markley, Lucas Horta, Manoranjan Majji, Andy Hung, and Je-Chin Han shared very kind words about our working experience. All of the photos and slides with quotations were stored in a Sony digital photo frame as a present for me to remember all of our fond memories. I was completely overwhelmed and touched, and could never have imagined anything of this magnitude occurring.

There are so many people to thank. First of all, I want to extend my gratitude and appreciation to the presenters and all attendees (some traveled from as far away as Taiwan and Korea) who came to hear the excellent talks. The symposium would not have taken place without the considerable efforts of the colleagues and friends: Richard Longman, John Crassidis, Terry Alfriend, James Turner, Minh Phan, Daniele Mortari, and John Valasek. The symposium was the highest technical meeting I have ever had the pleasure to attend.

Last but not least, I would like to express all my thanks to John Junkins, Lisa Willingham-Jordan, and Manoranjan Majji for their timeless and endless efforts in reviewing manuscripts and in organizing countless things including hotel reservations, registration, and the banquet. These efforts will continue until the final printing of these proceedings and a special issue of the *Journal of the Astronautical Sciences*.

Jer-Nan Juang

JER-NAN JUANG

BIOGRAPHY

Jer-Nan Juang is a Professor at the National Cheng Kung University (NCKU) of Taiwan since 2009. He is also an adjunct Professor at Texas A&M University. He was an Adjunct Chair Professor of National Chung-Hsing University and National Central University of Taiwan, and an Adjunct Professor of National Taiwan University. He served as the President of the National Applied Research Laboratories (NARL) of Taiwan. The majority of his professional career was with NASA Langley, where he conducted basic analytical and experimental research in the fields of system identification and control for engineering systems. He is the author of 2 textbooks, 6 patents, and over 200 technical publications including over 100 archival journal papers.

Jer-Nan received his BS degree from NCKU Department of Engineering Science in 1969. He came to the U.S.A. for his graduate study at Tennessee Technological University to major in engineering mechanics in 1970. His MS thesis under the guidance of Prof. John Peddieson was related to computational fluid dynamics focusing on computer simulations for the jet flow of a two-phase solid-fluid suspension. Jer-Nan's initial involvement in astrodynamics was a big surprise when Prof. Leonard Meirovitch invited him to be his Ph.D. student after taking his class on structural vibration at the Department of Engineering Sciences and Mechanics of Virginia Polytechnic Institute (VPI) in 1971. In 1974, he completed his Ph.D. dissertation on studying dynamic behavior of flexible spacecraft rotating in space, such as the Radio Astronomy Explorer (RAE) satellite. Landis Markley was his mentor when they worked as a contractor of NASA Goddard Flight Center from 1975 to 1977. Landis taught him spacecraft attitude determination in support of the Solar Maximum Mission (SMM). Mark Balas co-authored with Jer-Nan's first paper on feedback control of flexible structures as a result of Mark's control course at Martin Marietta Corporation, Denver, Colorado in 1979.

Jer-Nan joined NASA Langley Research Center in 1982. His first task, assigned by Larry Pinson and Brantley Hanks, was to develop system identification techniques for flexible spacecraft such as Galileo spacecraft. In 1984, he was appointed the leader of Optimum Performance Group in the Structural Dynamics Branch, responsible for coordinating joint research efforts with a variety of grantees and research fellows on a nationwide basis. Several system identification and control methods were developed, including Eigensystem Realization Algorithm (ERA; with Richard Pappa), ERA/DC (data correlation; with Jan Wright and Jonathan Copper), recursive ERA (with Richard Longman), optimal control with terminal constraints (with James Turner and Hon Chun), and robust pole placement techniques (with Kyong Lim, Peiman Maghami, and John Junkins). These methods were proposed starting from fundamental concepts and carrying out the theoretical developments completely through to experimental verification and useful level software. This was the most productive and creative period in research on control of large flexible structures. Many methods have had a tremendous impact on identification and control problems both in the U.S. and abroad. The 1985 ERA paper is the second most cited paper in the history of the *Journal of Guidance, Control, and Dynamics*. Recently, both ERA and OKID were extended to the time-varying ERA and time-varying OKID (with Manoranjan Majji and John Junkins in 2010) for identification of discrete-time varying linear systems.

From 1989 to 1991, Jer-Nan was the leader of the Test Methodology Team of the Control-Structures Integration (CSI) program. The CSI test team developed several ground test methods for verifying performance of integrated flexible structures-controls spacecraft systems. From 1989 to 2000, Jer-Nan was the Principal Scientist who guided the choice of research direction within the Structural Dynamics Branch, serving as consultant for many Branch research projects. He led the research activities on system identification and control. Jer-Nan was the principal developer of the Virtual Passive Controller (with Minh Phan) for control of linear or nonlinear flexible dynamical systems, the Observer/Kalman filter IDentification (OKID; with Lucas Horta, Minh Phan, and Richard Longman) and Observer/Controller IDentification (OCID; with Minh Phan) techniques. The OKID simultaneously identifies a system model and an optimal state estimator from input and output data. The OCID simultaneously identifies a system model, an optimal state estimator, and a controller from input, output and feedback data.

Jer-Nan also participated in many NASA research programs such as Advanced Subsonic Technology Noise Reduction (1995-2001), Geostationary Imaging Fourier Transform Spectrometer (GIFTS; 1998-2001), Wing and Rotor Aeroelastic Testing System (WRATS; 1996-2005), Development of Reduced-Order CFD Models for Use in Nonlinear Aeroservoelasticity (1999-2005), etc. Jer-Nan introduced a noise control approach combining System Identification with Generalized Predictive Control (GPC; with Kenneth Eure). The GPC method developed under the noise reduction program has been thoroughly studied including a series of wind-tunnel tests at Mach 0.8 and 2.5. Working with Raymond Kvaternik and Richard Bennett, a GPC-based MIMO (Multi-Input Multi-Output) active control system has been demonstrated to be highly effective in increasing ground resonance stability and reducing vibratory response for the WRATS. In collaboration with John Junkins, Thomas Pollock, and Hyong Kim, a new dual-head mini-star-tracker along with several pattern recognition methods was developed for the GIFTS. Developing compact and computationally efficient nonlinear, reduced-order CFD models amenable for use with modern control theory in nonlinear aeroservoelasticity problems motivated Jer-Nan's interest in nonlinear/bilinear system identification. He derived a new algorithm for identification of a continuous-time bilinear system in 2005. In this symposium, he and his student (Jason Lee) advanced the algorithm for the first time in the literature to establish a connection between the continuous-time and the discrete-time bilinear models via a specific input profile.

As President of NARL (2006-2008), Jer-Nan's responsibilities were fund raising and strategy planning for R&D platform integrations to facilitate infrastructure for academic research and industrial development in Taiwan ($200 Million US dollars per year). NARL, under Jer-Nan's leadership was recognized by Outstanding S&T Contribution Awards for 3 consecutive years by the Executive Yuan of Taiwan for its eco-grid technology, space technology, and high-performance computing platform software technology R&D. One Executive Yuan's Award for Outstanding Contributions in Science and Technology is a major national honor, 3 is a first.

Since 2009 in NCKU, Jer-Nan has broadened his research activities as evidenced by the three funded research projects: Intellignet Monitoring and control Microgrid DC Power Supply System, Simulation and Verification of Micro-Mechanical Systems (SVMS), and Establishment of an electrical Macrophage for Application to Biomedical Research. One of the SVMS tasks is dynamics and control of a solar sail with spinning membrane and so is a task proposed by Keats Wilkie of NASA Langley Research Center in the HELIOS (High-Performance, Enabling, Low-Cost, Innovative, Operational Solar Sail Spacecraft) program. Jer-Nan is currently a DRA (Distinguished Research Associate) of NASA Langley to help the HELIOS project.

Jer-Nan is the recipient of eleven NASA awards including the Exceptional Engineering Achievement Medal. He has received the following international Awards: the 1990 AAS Dirk Brouwer Award for outstanding contributions to space flight mechanics and astrodynamics, the 1993 AIAA Mechanics and Control of Flight Award, and the Best Paper Award at the 21st ASME Mechanisms Conference. He was elected a Distinguished Alumnus, National Cheng Kung University, Taiwan, 1995. He is a Fellow of the American Astronautical Society (AAS), the American Institute of Aeronautics and Astronautics (AIAA), and the American Society of Mechanical Engineers (ASME). He was a member of the editorial board of the *Journal of Vibration and Control*, and previously served as Associate Editor of the *Journal of the Astronautical Sciences*, the *Journal of Guidance, Control and Dynamics*, and the *Journal of Vibration and Acoustics*.

PREFACE

"Engineering research is really fun!" – Jer-Nan Juang

This phrase might seem trite until you witness the way Jer-Nan Juang works: Always with a smile, and you can feel the sheer joy he takes from making progress. Those of us privileged to work with Jer-Nan have witnessed first-hand much more than his "joy of work" mentality, we also appreciate greatly his generosity, intelligence, creativity, humor and tenacity. Jer-Nan is a towering one-of-a-kind personality and we all draw inspiration from the way he lives.

For four decades Jer-Nan Juang has proven recursively the validity of the words "there is nothing more practical than good theory." His work is at once fundamental and pragmatic. His most famous contributions in system identification were launched by his immortal Eigensystem Realization Algorithm (ERA) paper in 1985. The further related innovations that have flowed in the wake of the ERA contribution now represent, in our opinion, a vitally important modern branch of applied dynamical system theory (perhaps, second only to Rudy Kalman's immortal Kalman Filter).

This volume in the *Advances in the Astronautical Sciences* contains papers presented at the AAS Jer-Nan Juang Astrodynamics Symposium held June 24-26, 2012 at the College Station Hilton Hotel to honor Dr. Juang. The organizers thank the authors and all fifty participants for contributing to an outstanding and highly memorable event. We are pleased to acknowledge the sponsorship of AAS, Texas A&M University and Univelt, Inc. for publishing these proceedings. Special thanks are also due to Lisa Willingham (Jordan) for all of her administrative support of this symposium and to Elouise Junkins and Andreea Mortari for putting together a wonderful dinner that contributed greatly to the warmth of the interactions.

Most importantly this symposium offered an unforgettable occasion for Jer-Nan to inspire many young and young-at-heart colleagues with his special blend of competence, compassion, and humor. Jer-Nan's after-dinner presentation at the banquet was a wonderful punctuation mark for the symposium.

Jer-Nan, we salute you, we thank you, and we look forward to your future contributions.

Maruthi Akella	**Terry Alfriend**
John Crassidis	**John Junkins**
Richard Longman	**Manoranjan Majji**
Daniele Mortari	**Minh Phan**
James Turner	**John Valasek**

CONTENTS

STAY HUNGRY:
Plenary Presentation By Jer-Nan Juang

A HYBRID PARAMETER ESTIMATION ALGORITHM FOR S-SYSTEM MODEL OF GENE REGULATORY NETWORKS

Jer-Nan Juang* and Wesson Wu†

The reconstruction of a gene regulatory network expressed in terms of a S-system model may be accomplished by a simple task of parameter estimation. Empirical data indicate that biological gene networks are sparsely connected and the average number of upstream-regulators per gene is less than two, implying that most of parameter variables in the S-system model are zero. It is thus desired to search for a parameter estimation algorithm that is capable of identifying the connectivity of the gene network and determining its reduced number of non-zero parameters. A hybrid algorithm is presented for identification and parameter estimation of gene network structure described by a S-system model. It combines an optimization process with a system identification method commonly used in the aerospace community. Constraint equations in a matrix form are formulated to deal with the steady state and the network connectivity conditions. The system parameter vector resides in the null space of the constraint matrix. The resulting network structure and system parameters are optimally tuned by minimizing the error of state time history. A numerical experiment is given to illustrate the hybrid parameter estimation algorithm. [View Full Paper]

* Professor, Department of Engineering Science, National Cheng Kung University, Tainan City, Taiwan; Adjunct Professor, Aerospace Engineering Department, Texas A&M University, College Station, Texas 77843-3141, U.S.A.; Visiting Professor, National Institute of Aerospace, Hampton, Virginia 23666, U.S.A. Fellow AAS, AIAA, ASME.

† Assistant Professor, Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan.

SYSTEM IDENTIFICATION

SESSION 1

Chair: Minh Q. Phan
Dartmouth College

The following paper was not available for publication:

AAS 12-604
(Paper Withdrawn)

AAS 12-601

DYNAMICS OF A SLENDER SPINNING MEMBRANE

Jer-Nan Juang,* Chung-Han Hung† and William K. Wilkie‡

A novel approach is introduced to conduct dynamic analysis and system identification of a spinning, high aspect ratio membrane. In this formulation, an inextensible, long, slender membrane is modeled using a discrete set of lumped masses. Lagranges equations are used to derive the highly coupled ordinary differential equations for in-plane, out-of-plane, and twisting motions for the spinning membrane. The generalized and uncoupled linear equations for small motion are used to compute the vibration mode frequencies which are compared to results from an uncoupled analysis of blade motion using rotor dynamics. Linearized behavior is shown to reduce to the linearized solutions for the spinning membrane blade developed by MacNeal. Numerical simulations along with 3-D animations are used to study the linear and nonlinear uncoupled dynamics of the spinning membrane. [View Full Paper]

---

* Professor, Department of Engineering Science, National Cheng Kung University, Tainan City, Taiwan; Adjunct Professor, Aerospace Engineering Department, Texas A&M University, College Station, Texas 77843-3141, U.S.A.; Visiting Professor, National Institute of Aerospace, Hampton, Virginia 23666, U.S.A. Fellow AAS, AIAA, ASME.

† Graduate Student, Department of Engineering Science, National Cheng Kung University, Tainan City, Taiwan; Exchange Student, National Institute of Aerospace, Hampton, Virginia 23666, U.S.A.

‡ Head, Structural Dynamics Branch, NASA Langley Research Center, Hampton, Virginia 23681, U.S.A.

AAS 12-602

BATCH-FORM SOLUTIONS TO OPTIMAL INPUT SIGNAL RECOVERY IN THE PRESENCE OF NOISES

Ping Lin,[*] Minh Q. Phan[*] and Stephen A. Ketcham[†]

This paper studies the problem of optimally recovering the input signals to a linear time-invariant system when both input and measurement noises are present. We focus on batch-form solutions which are suitable for applications that deal with short-duration time series. The system, the input and measurement noise covariances, the noise-corrupted output signals are assumed known, and we seek to recover the input signals that enter the system prior to being corrupted by input noise. The proposed solution works through a Kalman filter to characterize the input and measurement noise statistics. The input signal recovery is optimal in the sense that the Kalman filter residual is correctly recovered from the given information about the model and the output measurements. A weighted least-squares solution is found to be both simple and useful in signal recovery applications. [View Full Paper]

* Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, U.S.A.

† Signature Physics Branch, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755, U.S.A.

UNCERTAINTY QUANTIFICATION OF THE EIGENSYSTEM REALIZATION ALGORITHM USING ANALYTICAL METHODS

Kumar Vishwajeet,[*] Manoranjan Majji[†] and Puneet Singla[‡]

This paper focuses on the development of analytical methods for uncertainty quantification of the models obtained by the Eigensystem Realization Algorithm (ERA) owing to the presence of noise in the input-output experimental data. Starting from first principles, analytical expressions are presented for the distribution of eigenvalues of the Hankel matrix by application of standard results in random matrix theory. This result naturally leads to a probabilistic method for model order determination (reduction). By application of further results from the theory of random matrices, we develop analytical expressions for the joint density of eigenvalues. These expressions enable us to construct the probability density functions of the identified linear models as a function of the uncertainties in test data. Numerical examples illustrate the applications of ideas presented in the paper. [View Full Paper]

* Graduate Student, Mechanical and Aerospace Engineering Department, University at Buffalo, Buffalo, New York 14260, U.S.A. E-mail: kumarvis@buffalo.edu.

† Assistant Professor, Mechanical and Aerospace Engineering Department, University at Buffalo, Buffalo, New York 14260, U.S.A. E-mail: mmajji@buffalo.edu. AAS Member, AIAA Member.

‡ Assistant Professor, Mechanical and Aerospace Engineering Department, University at Buffalo, Buffalo, New York 14260, U.S.A. E-mail: psingla@buffalo.edu. AAS Member, AIAA Senior Member.

DETERMINISTIC BILINEAR SYSTEM IDENTIFICATION

Cheh-Han Lee[*] and Jer-Nan Juang[†]

A unified identification method is proposed for system realization of the deterministic continuous-time/discrete-time bilinear models from input and output measurement data. A generalized Hankel matrix is formed with the output measurements obtained by applying a set of repeated input sequences to a bilinear system. A computational procedure is developed to extract a time varying discrete-time state-space model from the generalized Hankel matrix. The bilinear system models are realized by transferring the identified time varying discrete-time model to the bilinear models. Numerical simulations are given to show the effectiveness of the proposed identification method.
[View Full Paper]

* Graduate Student, Department of Engineering Science, National Cheng Kung University, Tainan, Taiwan.

† Professor, Department of Engineering Science, National Cheng Kung University, Tainan, Taiwan; Adjunct Professor, Texas A&M University, College Station, Texas 77843-3141, U.S.A. Fellow AAS, AIAA and ASME.

ATTITUDE DETERMINATION AND CONTROL

SESSION 2

Chair: Richard W. Longman
Columbia University

AAS 12-606

EVALUATION OF FIVE CONTROL ALGORITHMS FOR ADDRESSING CMG INDUCED JITTER ON A SPACECRAFT TESTBED

Edwin S. Ahn,* Richard W. Longman,† Jae J. Kim‡ and Brij N. Agrawal§

Spacecraft often experience jitter from reaction wheels, control moment gyros (CMGs), or from motion of other internal parts. One may isolate fine pointing equipment by passive techniques, but active vibration control employing knowledge of the periodic nature of jitter can improve performance. Previous work by the authors and co-workers tested active isolation using a 6 degree- of-freedom Stewart platform. A new class of applications is laser communication relay satellites, which replaces radio frequencies communication by laser communications. Laser beam jitter can be corrected by control of pan and tilt in fast steering mirrors. This paper develops experiments testing five candidate jitter cancellation algorithms on the Bifocal Relay Mirror Spacecraft, Three Axis Simulator 2 Testbed at the Naval Postgraduate School. Jitter results from the CMGs. Multiple period repetitive control (MPRC) and matched basis function repetitive control (MBFRC) are tested. Both use disturbance period information from Hall effect sensors for the CMG three phase brushless DC motors. Filtered-X LMS, adaptive linear model predictive control, and the Clearbox algorithm with Adaptive Basis Method are also tested. The best disturbance rejection resulted from the last of these choices, with a 66% overall amplitude reduction. Concerning MPRC it was discovered that repeating an addressed period can be used as a technique to decrease sensitivity to accurate knowledge of the disturbance period. [View Full Paper]

* Graduate Student, Mechanical Engineering Department, Columbia University, New York, New York 10027, U.S.A.

† Professor of Mechanical Engineering and Civil Engineering, Columbia University, New York, New York 10027, U.S.A.

‡ Research Assistant Professor, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93940, U.S.A.

§ Distinguished Professor, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93940, U.S.A.

AAS 12-607

PROSPECTS OF RELATIVE ATTITUDE CONTROL USING COULOMB ACTUATION

HANSPETER SCHAUB* and Daan Stevenson†

The relative attitude is studied between two charge controlled spacecraft being held at a fixed separation distance. While one body has a spherical shape, the 2nd body is assumed to be non-spherical and tumbling. The attitude control goal is to arrest the rotation of the 2nd body. While prior work has identified the existence of torques between charged bodies, this is the first analytical study on a charged feedback attitude control. Using the recently developed multi-sphere method to provide a simplified electrostatic force and torque model between non-spherical shapes, Lyapunov theory is used to develop a stabilizing attitude control using spacecraft potential as the control variable. Zero and non-zero equilibrium potentials are considered, with the later suitable for the electrostatic tug concept. With a pulling configuration, the cylinder will come to rest with the long axis aligned with the inter-vehicle axis in a stable configuration. For a pusher, the cylinder will settle 90 degrees rotated from this axis. Numerical simulations illustrate the control performance. [View Full Paper]

* Associate Professor, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, U.S.A.

† Graduate Research Assistant, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.

AAS 12-608

SWITCHED SYSTEMS FRAMEWORK FOR STABILIZATION SUBJECT TO UNKNOWN PIECE-WISE CONSTANT FEEDBACK DELAY

Apurva A. Chunodkar* and Maruthi R. Akella†

This paper considers the problem of stabilizing a class of nonlinear systems with unknown bounded delayed feedback wherein the time-varying delay is piecewise constant. We also consider application of these results to the stabilization of rigid-body attitude dynamics. The time-delay in feedback is modeled specifically as a switch among an arbitrarily large set of unknown constant values with a known strict upper bound. The feedback is a linear function of the delayed states. In the special case of linear systems with switched delay feedback, a new sufficiency condition for average dwell time result is presented using a complete type Lyapunov-Krasovskii (L-K) functional approach. Further, the corresponding switched system with nonlinear perturbations is proven to be exponentially stable inside a well characterized region of attraction for an appropriately chosen average dwell time. A constructive method to evaluate these new results is presented alongside comparisons with other sufficient stability conditions for delayed feedback from existing literature. Numerical simulations are performed to illustrate the theoretical results of this paper. [View Full Paper]

* Ph.D. Candidate, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Austin, Texas 78712, U.S.A.

† Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Austin, Texas 78712, U.S.A.

AAS 12-609

EQUIVALENCE OF TWO SOLUTIONS OF WAHBA'S PROBLEM

F. Landis Markley*

Many attitude estimation methods are based on an optimization problem posed in 1965 by Grace Wahba. All these methods will yield the same optimal estimate, except for inevitable computer roundoff errors. This note shows that Shuster's Quaternion Estimator (QUEST) and Mortari's Estimator of the Optimal Quaternion (ESOQ) are essentially identical even in the presence of computer roundoff errors. It also shows some connections between two other algorithms for solving Wahba's problem: Davenport's *q* method and the Singular Value Decomposition (SVD) method. [View Full Paper]

* Aerospace Engineer Emeritus, Attitude Control Systems Engineering Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A. E-mail: landis.markley@nasa.gov. Fellow AAS, Fellow AIAA.

GUIDANCE, NAVIGATION AND CONTROL

SESSION 3

Chair: Srinivas R. Vadali
Texas A&M University

The following paper was not available for publication:

AAS 12-617
(Paper Withdrawn)

THE SUCCESSIVE BACKWARD SWEEP METHOD FOR OPTIMAL CONTROL OF NONLINEAR SYSTEMS WITH CONSTRAINTS

D. H. Cho* and Srinivas R. Vadali†

This paper presents variations of the Successive Backward Sweep (SBS) method for solving nonlinear problems involving terminal and control constraints. The proposed SBS method is based on the linear quadratic control methodology and is relatively insensitive to the initial guesses of the state and control histories. The overall procedure of this method is similar to the existing neighboring extremals or differential dynamic programming algorithms. Several methods of Hessian modification are utilized, when required, to enable the backward integration of the gain equations. An "aiming point" variant of the sweep method is developed to satisfy the terminal constraints accurately. However, this method does not require consistency of the starting states and controls with respect to the system dynamics. Four numerical examples are considered to demonstrate the performance of SBS method and the results are compared to their respective open-loop counterparts. [View Full Paper]

* Graduate Student, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

† Stewart & Stevenson-I Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

AAS 12-611

FORMATION FLYING IMPULSIVE CONTROL USING MEAN ORBITAL SPEED

Sung-Hoon Mok,* Yoonhyuk Choi† and Hyochoong Bang‡

In this proceeding, an impulsive control method for satellite formation flying is introduced. Secular drift caused by mean orbital speed difference is used to decrease impulse magnitude and the drift motion is represented by mean anomaly difference among six orbital elements. Orbital elements illustrate orbital motion and simulation results show the control history. In addition, to validate the tendency of control history of previous research's method, optimization method is applied for same mission example. To use optimization method, relative dynamic equations are normalized by scale factors. Simulation studies investigate the performances of analytically proposed method and optimization method. The results show that the tendencies of orbital elements errors are similar between them. [View Full Paper]

* Ph.D. Candidate, Division of Aerospace Engineering, KAIST (Korea Advanced Institute of Science and Technology), Daejeon 305-701, Republic of Korea. E-mail: shmok@ascl.kaist.ac.kr.

† Postdoctoral Researcher, NASA Ames Research Center, Moffett Field, California 94035, U.S.A. E-mail: Yoonhyuk.choi@nasa.gov.

‡ Professor, Division of Aerospace Engineering, KAIST, Daejeon 305-701, Republic of Korea. E-mail: hcbang@ascl.kaist.ac.kr.

AAS 12-614

EVOLVING SYSTEMS: NONLINEAR ADAPTIVE KEY COMPONENT CONTROL WITH PERSISTENT DISTURBANCE REJECTION

Mark J. Balas* **and Susan A. Frost†**

This paper presents an introduction to Evolving Systems, which are autonomously controlled subsystems that self-assemble into a new Evolved System with a higher purpose. Evolving Systems of aerospace structures often require additional control when assembling to maintain stability during the entire evolution process. This is the concept of Adaptive Key Component Control which operates through one specific component to maintain stability during the evolution. In addition this control must overcome persistent disturbances that occur while the evolution is in progress. We present theoretical results for the successful operation of Nonlinear Adaptive Key Component control in the presence of such disturbances and an illustrative example. [View Full Paper]

* Electrical and Computer Engineering Department, University of Wyoming, 1000 E. University Ave., Laramie, Wyoming 82071, U.S.A. E-mail: mbalas@uwyo.edu.

† Intelligent Systems Division, NASA Ames Research Center, M/S 269-1, Moffett Field, California 94035, U.S.A. E-mail: susan.a.frost@nasa.gov.

AAS 12-627

DEVELOPMENT OF OPERATIONAL MODAL ANALYSIS TECHNIQUES FOR LAUNCH DATA

George James*

Correlation-based Operational Modal Analysis (OMA) has been used to act as a pathfinder for the development of techniques to process launch data. This activity, which emphasizes the estimation of modal damping, operates in an extremely challenging environment due to the rapidly changing modal properties, loading conditions, and vehicle configuration as well as the limited response data that is available. A historical review of these efforts is provided. Recent work with launch environment data has identified two issues for immediate attention: beat-like phenomena in the correlation functions of short time records and potential interactions between the vehicle control systems and extracted damping in the lowest bending modes of the vehicles. A working hypothesis and mitigation for the first problem (beat-like phenomena) has been developed but a convergence metric was needed. This paper provides a first generation metric to allow the development to continue. The second problem of potential control system interactions is still being scoped and has become the near-term driver for the development of higher-fidelity tools (as the beating mitigation). [View Full Paper]

* Aerospace Engineer, Loads and Structural Dynamics Branch, NASA Johnson Space Center, Houston, Texas 77058, U.S.A.

ORBIT DETERMINATION, NAVIGATION AND CONTROL

SESSION 4

Chair: John L. Junkins
Texas A&M University

AAS 12-612

ACCURATE KEPLER EQUATION SOLVER WITHOUT TRANSCENDENTAL FUNCTION EVALUATIONS

Adonis Pimienta-Peñalver[*] and John L. Crassidis[†]

The goal for the solution of Kepler's equation is to determine the eccentric anomaly accurately, given the mean anomaly and eccentricity. This paper presents a new approach to solve this very well documented problem. Here we focus on demonstrating the procedure for both the elliptical and hyperbolic cases. It is found that by means of a series approximation, an angle identity, the application of Sturm's theorem and an iterative correction method, the need to evaluate transcendental functions or store tables is eliminated. A 15th-order polynomial is developed through a series approximation of Kepler's equation. Sturm's theorem is used to prove that only one real roots exists for this polynomial for the given range of mean anomaly and eccentricity. An initial approximation for this root is found using a 3rd-order polynomial. Then a one time generalized Newton-Raphson correction is applied to obtain accuracies to the level of around 10^{-15} rad for the elliptical case and 10^{-13} rad for the hyperbolic case, which is near machine precision. [View Full Paper]

* Graduate Student, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York 14260-4400, U.S.A. E-mail: arp27@buffalo.edu.

† Professor, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York 14260-4400, U.S.A. E-mail: johnc@buffalo.edu. Member AAS.

AAS 12-615

SIMULATION BASED ORBIT UNCERTAINTY PROPAGATION

Sheng Cai,* Kai Yu,† Xin Dang‡ and Yang Cheng§

This paper presents a two-step, simulation based method to obtain a Gaussian mixture model for the non-Gaussian probability density of the orbital parameters. The first step involves generating random samples via Monte Carlo simulation. The second step reconstructs a Gaussian mixture model from the random samples using the Expectation-Maximization algorithm. Two alternative methods for generating random samples are considered: the Markov Chain Monte Carlo method and the stochastic collocation based generalized Polynomial Chaos method. A coupled orbit/attitude uncertainty propagation example and a circular restricted three-body example are used to demonstrate the viability of the method. [View Full Paper]

* Ph.D. Student, Department of Aerospace Engineering, Mississippi State University, Mississippi State, Mississippi 39762-5501, U.S.A.

† Ph.D. Student, Department of Mathematics, University of Mississippi, University, Mississippi 38677-1848, U.S.A.

‡ Associate Professor, Department of Mathematics, University of Mississippi, University, Mississippi 38677-1848, U.S.A.

§ Assistant Professor, Department of Aerospace Engineering, Mississippi State University, Mississippi State, Mississippi 39762-5501, U.S.A.

LYAPUNOV-BASED ELLIPTICAL TO CIRCULAR PLANAR ORBIT TRANSFERS IN LEVI-CIVITA COORDINATES

Sonia Hernandez,*[*] Maruthi R. Akella[†] and Cesar A. Ocampo[‡]

We consider planar orbit transfers around a central body using Lyapunov stability theory. The model used is the Levi-Civita transformation of the planar two-body problem. The advantage of working in these transformed coordinates is that the solution to the unperturbed equations of motion is that of a simple harmonic oscillator, so the analytical solution is known at all times during coast phases. We design a closed-loop guidance scheme for an orbit transfer from any initial elliptical orbit to a final circular orbit, utilizing a spacecraft with thrust-coast capabilities. The proposed Lyapunov functions give rise to asymptotically stabilizing control laws. The algorithm designed is robust, computationally fast, and can be used for both low- and high-thrust problems. Our new guidance solutions are seen to compare quite favorably to optimal orbit transfers using low thrust engines. [View Full Paper]

* Graduate Student, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, U.S.A. E-mail: sonia.hernandez@utexas.edu.

† Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, U.S.A. E-mail: makella@mail.utexas.edu.

‡ Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, U.S.A. E-mail: cesar.ocampo@mail.utexas.edu.

AAS 12-618

THREE-DIMENSIONAL TIME OPTIMAL MULTI-REVERSAL ORBIT BY USING HIGH PERFORMANCE SOLAR SAILS

Xiangyuan Zeng,[*] Kyle T. Alfriend[†] and Srinivas R. Vadali[‡]

In this paper a new family of three dimensional (3D) non-Keplerian orbits is produced by using a high performance solar sail. A sailcraft departs from Earth orbit in the ecliptic plane to accomplish a periodic trajectory with orbital angular momentum varying four times over one period. Such a new kind of orbit is referred to as a "multi-reversal orbit". It is symmetrical with respect to the plane which contains the Sun-perihelion line. Such a good property benefits the calculations and reduces the simulation effort. As a preliminary design, an ideal solar sail is adopted as well as a 3D dynamic model in the heliocentric inertial frame. In order to find the minimum periodic orbits, the problem is addressed in an optimal control framework solved by an indirect method. Two typical 3D multi-reversal orbits are obtained with different orbital constraints. The quasi-heliostationary condition near its two aphelion points, which are suitable for in-situ observations, is discussed. Its capability to obtain rectilinear trajectories not in the ecliptic plane is also demonstrated using numerical simulations. A comparison between these two typical orbits is conducted to show more details about this new orbit. Differences between the 3D multi-reversal orbit and double angular momentum reversal orbit are given to fully present the advantages of the multi-reversal concept. As a result of its attractive mission scenarios this new kind of orbit could enhance the development of sail technologies although the sail performance is beyond the current capabilities.

[View Full Paper]

* Ph.D. Candidate, School of Aerospace, Tsinghua University, China. E-mail: cengxy08@mails.tsinghua.edu.cn.

† Texas Engineering Experiment Station Distinguished Research Chair Professor, Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas, 77843-3141, U.S.A. E-mail: alfriend@tamu.edu.

‡ Stewart & Stevenson Professor, Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas, 77843-3141, U.S.A. E-mail: svadali@tamu.edu.

AAS 12-619

RECURSIVE IMPLEMENTATIONS OF THE CONSIDER FILTER

Renato Zanetti* and Chris D'Souza†

One method to account for parameters errors in the Kalman filter is to consider their effect in the so-called Schmidt-Kalman filter. This work addresses issues that arise when implementing a consider Kalman filter as a real-time, recursive algorithm. A favorite implementation of the Kalman filter as an onboard navigation subsystem is the UDU formulation. A new way to implement a UDU consider filter is proposed. The non-optimality of the recursive consider filter is also analyzed, and a modified algorithm is proposed to overcome this limitation. [View Full Paper]

* Senior Member of the Technical Staff, Vehicle Dynamics and Controls, The Charles Stark Draper Laboratory, 17629 El Camino Real, Suite 470, Houston, Texas, 77058, U.S.A. E-mail: rzanetti@draper.com.

† GN&C Autonomous Flight Systems Engineer, Aeroscience and Flight Mechanics Division, NASA Johnson Space Center, EG6, 2101 NASA Parkway, Houston, Texas, 77058, U.S.A. E-mail: chris.dsouza@nasa.gov.

DYNAMICAL SYSTEMS

SESSION 5

Chair: Maruthi R. Akella
University of Texas at Austin

AAS 12-620

ON NOETHER'S THEOREM AND THE VARIOUS INTEGRALS OF THE DAMPED LINEAR OSCILLATOR

Andrew J. Sinclair,[*] John E. Hurtado,[†] Chris Bertinato[‡] and Peter Betsch[§]

Noether's theorem provides deep insight into the connection between analytical mechanics and the integrals of dynamic systems, specifically, showing how symmetries of the action integral are connected to the integrals of motion. To demonstrate Noether's theorem, the harmonic oscillator is often used as a simple example problem. Presentations in the literature, however, often focus on the single absolutely-invariant symmetry for this problem. This paper presents a complete application of Noether's theorem to the damped harmonic oscillator, including general solutions of the divergence-invariant Killing equations and the associated integrals for all underdamped, critically-damped, and overdamped cases. This treatment brings forward several interesting issues. Five different symmetries produce independent solutions to the Killing equations, but of course, only two independent integrals exist for this second-order system. Also, integrals of a particular desired form may not be produced directly from Noether's theorem and are referred to as non-Noether or asymmetric integrals. For the damped oscillator, one such example is the time-independent integrals, referred to as motion constants. [View Full Paper]

* Associate Professor, Aerospace Engineering Department, Auburn University, 211 Davis Hall, Auburn, Alabama 36849, U.S.A.

† Associate Professor, Aerospace Engineering Department, Texas A&M University, 3141 TAMU, College Station, Texas 77843, U.S.A.

‡ Graduate Student, Aerospace Engineering Department, Texas A&M University, 3141 TAMU, College Station, Texas 77843, U.S.A.

§ Professor, Chair of Computational Mechanics, Department of Mechanical Engineering, University of Siegen, Siegen, Germany.

AAS 12-621

STATE-SPACE MODELING OF LARGE DOMAIN WAVE PROPAGATION SYSTEMS BY PARTITIONED C-MATRICES

Richard S. Darling,* Minh Q. Phan† and Stephen A. Ketcham‡

Reduced-order models represent an enabling technology in the representation of large-scale dynamic systems. This technology often involves identification of state-space models with system matrix A, input matrix B, and output matrix C. Our focus is partitioned C-matrices that facilitate creation of reduced-order discrete-time state-space models appropriate for simulation of large-output wave propagation systems. The Cy-partition method, used to generate the partitioned C-matrices, is suitable when the output dimension is orders of magnitude higher than the number of discrete time samples specifying the time duration of interest. The resulting state-space model is characterized by a relatively small C-matrix component relating a small number of "anchored" or basis outputs to the inputs, and a large C-matrix component relating all remaining outputs to the anchored outputs. The partitioned C-matrix and the associated A,B matrices can be identified from input-output data directly using time-domain signals, without the necessity of identifying or computing transfer functions. The resulting models can be used for accurate and rapid prediction of wavefield responses. The theory is general for modeling short-duration dynamics and the applications include modeling of vibrations propagating through a large flexible structure (for damage assessment for example). [View Full Paper]

* Research Mechanical Engineer, Signature Physics Branch, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, 72 Lyme Road, Hanover, New Hampshire 03755, U.S.A.

† Associate Professor, Thayer School of Engineering, Dartmouth College, 14 Engineering Drive, Hanover, New Hampshire 03755, U.S.A.

‡ Research Physical Scientist, Signature Physics Branch, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, 72 Lyme Road, Hanover, New Hamphsire 03755, U.S.A.

AAS 12-622

AN ITERATIVE PROPER ORTHOGONAL DECOMPOSITION (I-POD) TECHNIQUE WITH APPLICATION TO THE FILTERING OF PARTIAL DIFFERENTIAL EQUATIONS

Dan Yu* and Suman Chakravorty†

In this paper, we consider the filtering of systems governed by partial differential equations (PDE). We adopt a reduced order model (ROM) based strategy to solve the problem. We propose an iterative version of the snapshot proper orthogonal decomposition (POD) technique, termed I-POD, to construct ROMs for PDEs that is capable of capturing their global behaviour. Further, the technique is entirely data based, and is applicable to forced as well as unforced systems. We apply the ROM generated using the I-POD technique to construct reduced order Kalman filters to solve the filtering problem. The methodology is tested on several 1-dimensional PDEs of interest including the heat equation, the wave equation and randomly generated systems.
Keywords: Proper Orthogonal Decomposition (POD), Filtering/Data Assimilation, Partial Differential Equations. [View Full Paper]

* Graduate Student Researcher, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

† Associate Professor of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

AAS 12-623

STATISTICAL DYNAMICS OF LEARNING PROCESSES IN SPIKING NEURAL NETWORKS

David C. Hyland*

In previous work, the author and Dr. Jer-Nan Juang contributed a new neural net architecture, within the framework of "second generation" neural models. We showed how to implement backpropagation learning in a massively parallel architecture involving only local computations – thereby capturing one of the principal advantages of biological neural nets. Since then, a large body of neural-biological research has given rise to the "third-generation" models, namely *spiking neural nets,* wherein the brief, sharp pulses (spikes) produced by neurons are explicitly modeled. Information is encoded not in average firing rates, but in the temporal pattern of the spikes. Further, no physiological basis for backpropagation has been found, rather, synaptic plasticity is driven by the timing of spikes. The present paper examines the statistical dynamics of learning processes in spiking neural nets. Equations describing the evolution of synaptic efficacies and the probability distributions of the neural states are derived. Although the system is strongly nonlinear, the typically large number of synapses per neuron (~10,000) permits us to obtain a closed system of equations. As in the earlier work, we see that the learning process in this more realistic setting is dominated by local interactions; thereby preserving massive parallelism. It is hoped that the formulation given here will provide the basis for the rigorous analysis of learning dynamics in very large neural nets (10^{10} neurons in the human brain!) for which direct simulation is difficult or impractical.

[View Full Paper]

* Professor of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

ALGORITHMS AND METHODS

SESSION 6

Chair: Daniele Mortari
Texas A&M University

EVALUATION OF TWO CREW MODULE BOILERPLATE TESTS USING NEWLY DEVELOPED CALIBRATION METRICS

Lucas G. Horta* **and Mercedes C. Reaves***

The paper discusses a application of multi-dimensional calibration metrics to evaluate pressure data from water drop tests of the Max Launch Abort System (MLAS) crew module boilerplate. Specifically, three metrics are discussed: 1) a metric to assess the probability of enveloping the measured data with the model, 2) a multi-dimensional orthogonality metric to assess model adequacy between test and analysis, and 3) a prediction error metric to conduct sensor placement to minimize pressure prediction errors. Data from similar (nearly repeated) capsule drop tests shows significant variability in the measured pressure responses. When compared to expected variability using model predictions, it is demonstrated that the measured variability cannot be explained by the model under the current uncertainty assumptions. [View Full Paper]

* Aerospace Technologist, Structural Dynamics, NASA Langley Research Center, MS 230, Hampton, Virginia 23681, U.S.A.

AAS 12-624

A K-VECTOR APPROACH TO SAMPLING, INTERPOLATION, AND APPROXIMATION

Daniele Mortari* **and Jonathan Rogers†**

The **k**-vector search technique is a method designed to perform extremely fast range searching of large databases at computational cost independent of the size of the database. **k**-vector search algorithms have historically found application in satellite star-tracker navigation systems which index very large star catalogues repeatedly in the process of attitude estimation. Recently, the **k**-vector search algorithm has been applied to numerous other problem areas including non-uniform random variate sampling, interpolation of 1-D or 2-D tables, nonlinear function inversion, and solution of systems of nonlinear equations. This paper presents algorithms in which the **k**-vector search technique is used to solve each of these problems in a computationally-efficient manner. In instances where these tasks must be performed repeatedly on a static (or nearly-static) data set, the proposed **k**-vector-based algorithms offer an extremely fast solution technique that outperforms standard methods. [View Full Paper]

Truth is much too complicated to allow anything but approximations (John von Newman, 1947).

* Professor, 746C H.R. Bright Bldg, Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A. Tel.: (979) 845-0734, Fax: (979) 845-6051, AIAA Associate Fellow. IEEE senior member. E-mail: MORTARI@TAMU.EDU.

† Assistant Professor, 746B H.R. Bright Bldg, Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A. Tel.: (979) 862-3413, Fax: (979) 845-6051. E-mail: JROGERS@AERO.TAMU.EDU.

STREAMILINING ASTRONAUTICAL ENGINEERING EDUCATION THROUGH THE USE OF INTERNET-BASED COURSE AND CUBESAT PROJECT

Jiun-Jih Miau,* Jyh-Ching Juang† and Yung-Fu Tsai‡

Foreword: In 2003-2008, Professor Jer-Nan Juang who served as the Director General of the National Center for High-performance Computing and later as the President of National Applied Research Laboratory, Taiwan, had played a key role in promoting astronautical and system engineering education in Taiwan. The paper highlights some activities and accomplishments of the internet- based course that Professor J. N. Juang helped to setup.

Abstract: The paper presents a comprehensive discussion on the use of internet-based picosatellite system engineering course and cubesat project-based learning as an educational and research tool in promoting astronautical science and system engineering education. Traditionally, space science and engineering education being a multi-disciplinary subject is noted by the lack of hands-on experiences and project-based training at the university-level curriculum. The situation is even worse in Taiwan as experts in different disciplines are not clustered at one university. To mitigate these limitations and facilitate the resources in industry, an internet-based course was offered at an inter-university level in Taiwan. The course was organized in such a manner that experts in industry and professors in different universities shared the teaching load and students were grouped to conduct their own design projects. Cubesat design was assigned as the term project for students to gain hands-on experience in design and analysis at the system and subsystem levels, as well as implementation. The paper first reviews recent development in cubesats around different universities in the world. This is followed by some discussions on the development of the internet-based course for students to learn and practice. Then, a report on the current status of the PACE (Platform for Attitude Control Experiment) satellite project, which was motivated by this internet course, is provided. Finally, a future outlook on the international collaboration of space engineering education and research based on the experiences gained in the past ten years is given. [View Full Paper]

* Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan, Taiwan. E-mail: jjmiau@mail.ncku.edu.tw.

† Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan. E-mail: juang@mail.ncku.edu.tw.

‡ Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan.

AAS 12-626

GENERALIZED ALGORITHMS FOR LEAST SQUARES OPTIMIZATION FOR NONLINEAR OBSERVATION MODELS AND NEWTON'S METHOD

Ahmad Bani Younes* and James D. Turner†

Many problems in science and engineering must solve nonlinear necessary conditions for defining meaningful solutions. For example, a standard problem in optimization involves solving for the roots of nonlinear functions defined by f(x) = 0, where x is the unknown variable. Classically one develops a first-order Taylor series model which provides the necessary condition that must be iteratively solved. The success of this approach depends on the validity of the assumption that the correction terms are small. Two classes of problems arise: (1) non-square systems that lead to least-squares solutions, and (2) square systems that are often handled by Newton-like methods. Both problem classes are sensitive to the accuracy of the starting guess, which impacts the number of iteration cycles required for achieving desired accuracy goals. As problems become more nonlinear, both approaches are generalized by permitting first- through fourth-order approximations. Computational differentiation tools are used form computing the partial derivatives. Two solution approaches are presented: (1) a Legendre transformation, and (2) a generalized linear algebra approach for handling tensor equations. Several numerical examples are presented to demonstrate generalized multilinear algebra solution algorithms for Least-Squares and Newton-Raphson Methods. Accelerated convergence rates are demonstrated for scalar and vector root-solving problems. The integration of generalized algorithms and automatic differentiation is expected to have broad potential for impacting the design and use of mathematical programming tools for knowledge discovery applications in science and engineering. [View Full Paper]

* Ph.D. Candidate, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: olalahmad@gmail.com.

† Research Professor, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. Tel. 979-458-1429. E-mail: turner@aero.tamu.edu. Fellow AAS, Associate Fellow AIAA.

DECISIONS IN PREDICTIVE LOCATION AND MAPPING

Manoranjan Majji[*] and John L. Junkins[†‡]

This paper presents our recent progress in simultaneous localization and mapping. Discussing recent progress in algorithms for dense reconstruction of unstructured environments and robust self-navigation, we present our work along with a variety of applications. In the light of this discussion, it is felt that the fusion of computational vision with control can now be contemplated on the near horizon. Key challenges that enable this information driven fusion are presented in the paper. Some preliminary analysis and associated results are presented on the topics of bundle adjustment, feature based navigation and object space tracking to report progress in addressing the key challenges identified. Some experimental test results are presented to document the efficacy of the algorithms presented in the paper. Prefatory experiments on kinect based proximity spacecraft motion emulation experiments are shown to demonstrate the challenges outlined in the paper. [View Full Paper]

* Assistant Professor, Mechanical and Aerospace Engineering Department, The University at Buffalo, 318 Jarvis Hall, Buffalo, New York 14260, U.S.A.

† Regents Professor, Distinguished Professor, Royce E. Wisenbaker Chair in Engineering, Aerospace Engineering Department, Texas A&M University, 3141-TAMU, College Station, Texas 77843-3141, U.S.A.

‡ **Dedicated to our friend and colleague Jer-Nan Juang, celebrating his contributions to spacecraft dynamics and control**.

INTERACTIVE PRESENTATIONS

INTERACTIVE PRESENTATIONS SESSION

The following paper was not available for publication:

AAS 12-635

(Paper Withdrawn)

AAS 12-628

UNCERTAINTY QUANTIFICATION OF THE EIGENSYSTEM REALIZATION ALGORITHM USING THE UNSCENTED TRANSFORM

Martin Diz,* Manoranjan Majji† and Puneet Singla‡

In this study, we present a systematic procedure to compute the identified model parameter uncertainties as functions of the statistics of input and output experimental data obtained using the celebrated Eigensystem Realization Algorithm (ERA). An Unscented Transformation (UT) is applied to map the error statistics from the input-output test signal space of the test data to the plant parameter space. It is shown that a computationally efficient algorithm is obtained by an application of the unscented transformation in a high dimensional space. Outputs of the algorithm include the mean and covariance estimates of the identified plant parameters obtained through the Observer/Kalman Filter Identification (OKID) calculations followed by ERA. Numerical simulations and comparisons with Monte-Carlo error statistics demonstrate the efficacy of the unscented transformation presented in this paper. [View Full Paper]

* Graduate Research Assistant, Mechanical and Aerospace Engineering Department, State University of New York University at Buffalo, Buffalo, New York 14260, U.S.A. E-mail: martindi@buffalo.edu.

† Assistant Professor, Mechanical and Aerospace Engineering Department, State University of New York University at Buffalo, Buffalo, New York 14260, U.S.A. E-mail: mmajji@buffalo.edu.

‡ Assistant Professor, Mechanical and Aerospace Engineering Department, State University of New York University at Buffalo, 318 Jarvis Hall, Buffalo, New York 14260. E-mail: psingla@buffalo.edu.

AAS 12-629

USING CARLEMAN EMBEDDING TO DISCOVER A SYSTEM'S MOTION CONSTANTS

John E. Hurtado* and Andrew J. Sinclair†

Although the solutions with respect to time are commonly sought when analyzing the behavior of dynamic systems, there are other expressions that can be as revealing and important. Specifically, motion constants, which are time independent algebraic or transcendental equations involving the system states, can provide a broad view of a system's motion. Locally, at least, the motion constants of autonomous systems exist. Nevertheless, for finite dimensional, autonomous, nonlinear systems, the motion constants are generally difficult to identify. The motion constants for every finite dimensional, autonomous, linear system, regardless of its dimension, however, have recently been found. This paper attempts to discover the motion constants of nonlinear systems through the motion constants of a linear representation. The linear representation is achieved through a Carleman embedding, which provides a procedure to transform a finite dimensional system of analytic ordinary differential equations into an infinite system of linear differential equations. [View Full Paper]

* Associate Professor, Aerospace Engineering Department, Texas A&M University, 3141 TAMU, College Station, Texas 77843, U.S.A.

† Associate Professor, Aerospace Engineering Department, Auburn University, 211 Davis Hall, Auburn, Alabama 36849, U.S.A.

THIRD-BODY PERTURBATION EFFECTS ON SATELLITE FORMATIONS

Christopher W. T. Roscoe,[*] Srinivas R. Vadali[†] and Kyle T. Alfriend[‡]

The effects of third-body perturbations on satellite formations are investigated using differential orbital elements to describe the relative motion. Absolute and differential effects of the lunar perturbation on satellite formations are derived analytically based on the simplified model of the circular restricted three-body problem. This analytical description includes averaged long-term effects on the orbital elements, including the full transformation between the osculating elements and the lunar-averaged elements, which is absent from previous research. A simplified Earth-Moon system model is used, but the results are applicable to any formation reference orbit about the Earth. Simulations are performed to determine the effects of the lunar perturbation on example formations in upper MEO, highly eccentric orbits by using the formation design criteria of Phases I and II of the NASA Magnetospheric Multiscale mission. The changes in angular differential orbital elements ($\delta\omega$, $\delta\Omega$, and δM_0) and in science return quality due to this perturbation are compared to changes due to J_2, and the results are compared to simulation using the NASA General Mission Analysis Tool. [View Full Paper]

* Graduate Student, Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas, 77843-3141, U.S.A. E-mail: c.roscoe@tamu.edu.

† Stewart & Stevenson Professor, Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas, 77843-3141, U.S.A. E-mail: svadali@tamu.edu.

‡ Texas Engineering Experiment Station Distinguished Research Chair Professor, Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas, 77843-3141, U.S.A. E-mail: alfriend@tamu.edu.

AAS 12-632

REALIZATION OF STATE-SPACE MODELS FOR WAVE PROPAGATION SIMULATIONS

Stephen A. Ketcham,* Minh Q. Phan,† Richard S. Darling‡ and Mihan H. McKenna§

Fully three-dimensional numerical solutions can quantify exterior seismic or acoustic propagation throughout complex geologic or atmospheric domains. Results from impulsive sources typically reveal propagating waves plus reverberations typical of multi-path scattering and wave-guide behavior, with decay toward quiescent motions as the dominant wave energy moves out of the domain. Because such computations are expensive and yield large data sets, it is advantageous to make the data reusable and reducible for both direct and reciprocal simulations. Our objective is efficient time-domain simulation of the wave-field response to sources with arbitrary time series. For this purpose we developed a practical and robust technique for superstable model identification. A superstable model has the form of a state-space model, but the output matrix contains the system dynamics. It simulates propagation with the fidelity of the pulse response calculated for the numerical system. Our development of the superstable technique was motivated by our initial application of the Eigensystem Realization Algorithm to wave-field systems from high-performance- computing analyses, where we recognized exterior propagation features allowing superstable model assignment. Most importantly the pulse response and its decay over the domain are captured in a finite duration, and decay to zero beyond a finite number of time steps implies a system with zero eigenvalues. We demonstrate propagation-system identification with pulse response data derived from supercomputer analysis, and conclude that, using superstable-identified systems, we are able to create reusable and reducible propagation-system models that accurately simulate the wave field using a fraction of the original computational resources. [View Full Paper]

* Research Physical Scientist, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, 72 Lyme Road, Hanover, New Hampshire 03755, U.S.A.

† Associate Professor, Thayer School of Engineering, Dartmouth College, 14 Engineering Drive, Hanover, New Hampshire 03755, U.S.A.

‡ Research Mechanical Engineer, Signature Physics Branch, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, 72 Lyme Road, Hanover, New Hampshire 03755, U.S.A.

§ Research Geophysicist, Geotechnical and Structures Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, Mississippi 39180, U.S.A.

AAS 12-633

THE ROLE OF TOTAL LEAST SQUARES IN THE COMMON ATTITUDE ESTIMATION PROBLEM

Kurt A. Cavalieri[*] and John E. Hurtado[†]

Single point attitude determination is the problem of estimating the instantaneous attitude of a rigid body from a collection of vector observations taken at a single moment in time. Traditionally, vector measurements are compared to some known model that is assumed to be error free. Several solutions have been developed since Wahba first proposed the problem. Each technique takes a unique approach to the attitude estimation problem and solutions can be expressed using a variety of attitude parameters. More recently, the relative attitude estimation problem has gained attention which assumes measurement errors are present in both sets of vector observations. The discussed techniques use a familiar least squares approach, but the nature of the relative attitude problem suggests that a total least squares approach is more appropriate. Thus, the role of total least squares in relative attitude estimation is investigated through numerical examples. [View Full Paper]

* Graduate Research Assistant, Aerospace Engineering Department, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

† Associate Professor, Aerospace Engineering Department, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

ORTHOGONAL POLYNOMIAL APPROXIMATION IN HIGHER DIMENSIONS: APPLICATIONS IN ASTRODYNAMICS

John L. Junkins,* Ahmad Bani Younes† and Xiaoli Bai‡

We unify and extend classical results from function approximation theory and consider their utility in astrodynamics. Least square approximation, using the classical Chebyshev polynomials as basis functions, is reviewed for discrete samples of the to-be-approximated function. We extend the orthogonal approximation ideas to n-dimensions in a novel way, through the use of array algebra and Kronecker operations. Approximation of test functions illustrates the resulting algorithms and provides insight into the errors of approximation, as well as the associated errors arising when the approximations are differentiated or integrated. Two sets of applications are considered that are challenges in astrodynamics. The first application addresses local approximation of high degree and order geopotential models, replacing the global spherical harmonic series by a family of locally precise orthogonal polynomial approximations for efficient computation. A method is introduced which adapts the approximation degree radially, compatible with the truth that the highest degree approximations (to ensure maximum acceleration error $<10^{-9}$ m/sec^2, globally) are required near the Earth's surface, whereas lower degree approximations are required as radius increases. We show that a four order of magnitude speedup is feasible, with efficiency optimized using *radial adaptation*. The second class of problems includes orbit propagation and solution of associated boundary value problems. The Chebyshev-Picard path approximation method is shown well-suited to solving these problems with over an order of magnitude speedup relative to known methods. Furthermore, the approach is parallel-structured so that it is suited for parallel implementation and further speedups. Used in conjunction with orthogonal FEM gravity approximations, the Chebyshev-Picard path approximation enables truly revolutionary speedups in orbit propagation without accuracy loss. [View Full Paper]

---

* Distinguished Professor, Texas A&M University, Aerospace Engineering Department, 722 H.R. Bright Build-ing, 3141 TAMU, College Station, Texas 77843-3141, U.S.A.
E-mail: junkins@tamu.edu. Tel. 979-845-3912; Fellow AAS.

† Graduate Research Assistant, Texas A&M University, Aerospace Engineering Department, 701 H.R. Bright Building, 3141 TAMU, College Station Texas 77843-3141, U.S.A.
E-mail: olalahmad@gmail.com. Tel. 979-845-3912.

‡ Scientist, Optimal Synthesis, Inc., 95 1st Street, Suite 240, Los Altos, California 94022, U.S.A.
E-mail: xiaolibai@optisyn.com. Tel. 650-559-8585.

AAS 12-636

HIGH-ORDER UNCERTAINITY PROPAGATION USING STATE TRANSITION TENSOR SERIES

Ahmad Bani Younes,[*] James D. Turner,[†] Manoranjan Majji[‡] and John L. Junkins[§]

Modeling and simulation for complex applications in science and engineering develop behavior predictions based on mechanical loads. Imprecise knowledge of the model parameters or external force laws alters the system response from the assumed nominal model data. As a result, one seeks algorithms for generating insights into the range of variability that can be the expected due to model uncertainty. Two issues complicate approaches for handling model uncertainty. First, most systems are fundamentally nonlinear, which means that closed-form solutions are not available for predicting the response or designing control and/or estimation strategies. Second, series approximations are usually required, which demands that partial derivative models are available. Both of these issues have been significant barriers to previous researchers, who have been forced to invoke computationally intense Monte-Carlo methods to gain insight into a systems nonlinear behavior through a massive sampling process. These barriers are overcome by introducing three strategies: (1) Computational differentiation that automatically builds exact partial derivative models; (2) Automatic development of state transition tensor series-based solution for mapping initial uncertainty models into instantaneous uncertainty models; and (3) Development of nonlinear transformations for mapping an initial probability distribution function into a current probability distribution function for computing fully nonlinear statistical system properties. The resulting nonlinear probability distribution function (*pdf*) represents a *Liouiville* approximation for the stochastic *Fokker Planck* equation. Several applications, using nonlinear systems, are presented that demonstrate the effectiveness of the proposed mathematical developments, where the solution is validated by using a Mont-Carlo simulation method. A nonlinear covariance algorithm is presented that uses a closed-form solution for evaluating the expectation values of high-order tensor models for Gaussian variables. The general modeling methodology is expected to be broadly useful for science and engineering applications in general, as well as grand challenge problems that exist at the frontiers of *computational science and mathematics*. [View Full Paper]

* Ph.D. Candidate, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: olalahmad@gmail.com.

† Research Professor, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: turner@aero.tamu.edu. Fellow AAS, Associate Fellow AIAA.

‡ Assistant Professor, Mechanical and Aerospace Engineering Department, University at Buffalo, Buffalo, New York 14260, U.S.A.

§ Distinguished Professor, Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A. E-mail: junkins@tamu.edu. Fellow AAS, Fellow AIAA.

HIGH-ORDER STATE FEEDBACK GAIN SENSITIVITY CALCULATIONS USING COMPUTATIONAL DIFFERENTIATION

Ahmad Bani Younes,* James D. Turner,† Manoranjan Majji‡ and John L. Junkins§

A nonlinear feedback control strategy is presented where the feedback control is augmented with feedback gain sensitivity partial derivatives for handling model uncertainties. Derivative enhanced optimal feedback control is shown to be robust to large changes in the model parameters. The OCEA (Object Oriented Coordinate Embedding) computational differentiation toolbox is used for automatically generating first- through fourth-order partial derivatives for the feedback gain differential equation. Both linear and nonlinear scalar applications are presented. The model sensitivities are obtained about a nominal reference state by defining the Riccati differential equation as being derivative enhanced: OCEA then automatically generates the first- through fourth-order Riccati gain gradients. An estimator is assumed to be available for predicting the model parameter changes. The optimal gain is then computed as a Taylor series expansion in the Riccati gain as a function of the system model parameters. The pre-calculation of the sensitivity gains eliminates the need for gain scheduling for handling model parameter changes. Examples are presented that demonstrate the impact of nonlinear response behaviors, as well as the effectiveness of the generalized sensitivity enhanced feedback control strategy. [View Full Paper]

* Ph.D. Candidate, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: olalahmad@gmail.com.

† Research Professor, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: turner@aero.tamu.edu. Fellow AAS, Associate Fellow AIAA.

‡ Assistant Professor, Mechanical and Aerospace Engineering Department, University at Buffalo, Buffalo, New York 14260, U.S.A.

§ Distinguished Professor, Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A. E-mail: junkins@tamu.edu. Fellow AAS, Fellow AIAA.

AAS 12-638

NUMERICAL INTEGRATION OF CONSTRAINED MULTI-BODY DYNAMICAL SYSTEMS USING 5TH ORDER EXACT ANALYTIC CONTINUATION ALGORITHM

Ahmad Bani Younes* **and James D. Turner†**

Many numerical integration methods have been developed for predicting the evolution of the response of dynamical systems. Standard algorithms approach approximate the solution at a future time by introducing using a truncated power series representation that attempts to recover an n-th order Taylor series approximation, while only numerically sampling a single derivative model. An exact fifth-order analytic continuation method is presented for integrating constrained multibody vector-valued systems of equations, where the *Jacobi form of the Routh-Voss* equations of motion simultaneously generates the acceleration and Lagrange multiplier solution. The constraint drift problem is addressed by introducing an analytic continuation method that rigorously enforces the kinematic constraints through five time derivatives. The proposed approach is expected to be particularly useful for stiff dynamical systems, as well as systems where implicit integration formulations are introduced. Numerical examples are presented that demonstrate the effectiveness of the proposed methodology. [View Full Paper]

* Ph.D. Candidate, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: olalahmad@gmail.com.

† Research Professor, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: turner@aero.tamu.edu. Fellow AAS, Associate Fellow AIAA.

AAS 12-639

HIGH-ORDER ANALYTIC CONTINUATION AND NUMERICAL STABILITY ANALYSIS FOR THE CLASSICAL TWO-BODY PROBLEM

Tarek Elgohary,* James D. Turner† and John L. Junkins‡

Several methods exist for integrating the Keplerian Motion of two gravitationally interacting bodies. Lagrange introduced three vector-valued invariants that allowed the position and velocity vectors to be expanded. Alternatively, the classical F & G Lagrangian coefficients provide a mapping of the initial position and velocity into current time values. Nevertheless, classically, it has proven difficult to develop high-order Taylor series expansions, even though the governing equations are well-defined. This work presents two scalar Lagrange-like invariants ($f = r \cdot r$ *and* $g = f^{-n/2}$) that enable all of the higher-order vector-valued derivatives to be recursively evaluated using Leibniz product rule. The calculations for the higher-order trajectory derivatives are developed by deriving a differential equation for g that eliminates fractional powers. The basic methodology is extended to handle perturbed acceleration force models for the J_2 zonal gravity harmonic term. The approach is both efficient and accurate. The two-body problem is handled by computing $\ddot{r} = -\mu r g$, where r = [x,y,z] denotes the inertial relative coordinate vector that locates an object relative to the Earth and μ = 398601.2 km^2/sec^2 is the gravitational constant. Given $r, \dot{r}, \ddot{r}$ Leibniz product rule is used to recursively develop $\{\dot{f}, \dot{g}, \dddot{r}\}, \{\ddot{f}, \ddot{g}, \ddddot{r}\}, \cdots$. Series convergence issues are addressed by invoking a vector version of a Padé series approximation for each component of the vector-valued Taylor series $r(t+h) = r(t) + \dot{r}(t)h + \ddot{r}(t)h^2/2! + \dddot{r}(t)h^3/3! + \cdots$. The behavior of the Padé roots is studied as a function of the number of derivative terms retained in the series approximation and solution accuracy for the series approximation. Numerical results are presented that compare the solution accuracy and integration time required by *ODE45* and *RKN1210*, and the analytic power series methods developed in this work for two-body plus J_2 perturbation terms. [View Full Paper]

* Graduate Student, Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141.

† Research Professor, Aerospace Engineering, Texas A&M University, 745 HR Bright Building, 3141 TAMU College Station, Texas 77843-3141, U.S.A. E-mail: turner@aero.tamu.edu. Fellow AAS, Associate Fellow AIAA.

‡ Distinguished Professor, Texas A&M University, Aerospace Engineering Department, 722 H.R. Bright Build-ing, 3141 TAMU, College Station, Texas 77843-3141, U.S.A.
E-mail: junkins@tamu.edu. Tel. 979-845-3912; Fellow AAS.

AAS 12-640

SPACECRAFT ATTITUDE CONTROL USING TWO CONTROL TORQUES

Donghoon Kim* and James D. Turner†

All spacecraft are designed to be maneuvered to achieve pointing goals. This is accomplished by designing a three-axis control system which can achieve arbitrary maneuvers, where the goal is to repoint the spacecraft and suppress the residual angular velocity at the end of the maneuver. If one of the three-axis control actuators fails then new control laws are required. This paper explores optimal maneuver strategies when only two control torques are available. A key algorithm development is concerned with identifying maneuver switch times for transitioning the control inputs between the remaining control devices. Numerical results are presented that compare optimal maneuver strategies for both nominal and failed actuator cases. [View Full Paper]

* Ph.D. Student, Aerospace Engineering, Texas A&M University, 301B Reed McDonald Building, 3141 TAMU College Station, Texas 77843-3141, U.S.A.

† Research Professor, Aerospace Engineering, Texas A&M University, 745 HR Bright Building, 3141 TAMU College Station, Texas 77843-3141, U.S.A. E-mail: turner@aero.tamu.edu. Fellow AAS, Associate Fellow AIAA.

AAS 12-641

ON THE INTEGRATION OF M-DIMENSIONAL EXPECTATION OPERATORS

James D. Turner* and Ahmad Bani Younes†

A general expectation theorem of Isserlis (1916,1918) provides a structure for evaluating m-dimensional expectation operators for systems governed by Gaussian random variables. This works well when the order of the expectation operator is < 4. When the order of the expectation operator is > 4, the calculations required to apply Isserlis theorem become unwieldy. Symbolic computer algebra is used to automate the generation of arbitrary order expectation operator calculations. The algorithm consists of developing a closed-form integral expression that is repeatedly differentiated with an artificial parameter, and evaluated in a limit condition to yield the desired m-dimensional expectation operator. The symbolic results are cross checked by performing a hyper-spherical coordinate transformation which is evaluated in closed-form. [View Full Paper]

* Research Professor, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: turner@aero.tamu.edu. Fellow AAS, Associate Fellow AIAA.

† Ph.D. Candidate, Aerospace Engineering, Texas A&M University, College Station, Texas, 77843-3141, U.S.A. E-mail: olalahmad@gmail.com.