THE KYLE T. ALFRIEND
ASTRODYNAMICS SYMPOSIUM

Front Cover Illustration:

Terry's Space Lab by Brandon Alfriend.

THE KYLE T. ALFRIEND ASTRODYNAMICS SYMPOSIUM

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ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Shannon L. Coffey
John L. Junkins
K. Kim Luu
I. Michael Ross
Chris Sabol
Paul W. Schumacher, Jr.

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FOREWORD

There is no greater honor than to have your friends, colleagues, and family come to celebrate and acknowledge ones contributions and life's work. I would like to think that they would have come to the symposium regardless of the fact that it was held on the beautiful Monterey Peninsula, and in the Monterey Plaza Hotel. As the symposium approached I was very excited, but my exuberance prior to the event paled in comparison to that when it occurred. I was completely humbled, and overwhelmed. Years into my career I never could have imagined anything of this magnitude occurring.

There are so many people to thank, and in this process one always risks leaving someone out. Let me apologize upfront if I have been remiss in not naming everyone. I must start with Kim Luu and Chris Sabol, who not only suggested the symposium, but offered to take charge of the entire process. Kim, who has been General Chair for several AAS Space Flight Mechanics Conferences, had stated emphatically she would never do one again, jumped in and did her usual extraordinary job. Chris took charge of the technical portion and enlisted the help of four long time friends and colleagues, Shannon Coffey, John Junkins, Paul Schumacher, and Mike Ross, whom I have worked with extensively over many years. Mike being a Monterey resident also helped with some of the local details. This technical team put together one of the highest quality technical meetings I have ever had the pleasure to attend.

I want to extend my heart felt gratitude and appreciation to all who came; the presenters and all attendees who came to hear the excellent talks. It started with a nice introduction by John Junkins. Jer-Nan Juang came all the way from Taiwan, and brought one of his graduate students. He also presented me with a beautiful Taiwan dragon puppet. Thank you, Jer-Nan. Antonio Elipe and Sebastion Ferrer endured the long trip from Spain. A special thank you to them for coming so far. I was very pleased that my long time friend Richard Longman could attend. Bonnie credits him with training me on how to work all night. Shortly after the symposium Richard's lovely and talented wife Marilyn passed away suddenly. We all mourn with him. I also want to thank those who could not come but sent cards and emails of congratulations and accolades. My thanks to my local friends who took the time to attend the reception and final banquet. I especially appreciate my daughter Kim, my son Kyle and two of his four sons, Travis and Erik, for traveling to Monterey. Having my family present made this event even more special. I have saved the most important person to last; my wonderful wife, life long companion and friend, Bonnie. She makes it all worthwhile. All my thanks to her for organizing the reception and putting up with me for all these years.

The banquet was a grand finale to the entire symposium. I want to thank my friends for not roasting me too badly, I was expecting much worse. We experienced great eloquence by Paul Schumacher reading a poem by Lord Tennyson. Ken Seidelmann presented me with a copy of his new book. Ken and I have been General and Technical Chairs of the US/Russian Space Surveillance Workshops and it has been a real pleasure working with him. My Russian colleagues from the work shops sent me a beautiful 70th birthday card and gift that I will treasure. Everyone was able to hear my son speak with a sense of humor that he gets from his mother, not me. Kyle also presented me with a picture painted by my oldest grandson, Brandon, who was unable to attend. This picture provided the cover illustration for these proceedings. Finally my grandson Travis presented me with the book *Rocket Man*; a gift from all four of my grandsons. What a great finish to the most extraordinary event of my professional career! Thank you one and all.

Terry Alfriend

KYLE T. ALFRIEND

BIOGRAPHY

Terry Alfriend was born in Macon, GA, and raised in Danville, VA. During his youth he concentrated on sports with a desire to be a professional baseball or football player. Fortunately for the field of astrodynamics, he realized that this early dream was not a viable option and that he had to seek a different avenue to support himself as an adult. He decided to attend Virginia Polytechnic Institute (now called Virginia Tech) and, because he had enjoyed math and physics, to major in engineering, even though up to that point in his life he had never met an engineer. He became very interested in his sophomore mechanics courses and decided to major in engineering mechanics. Terry's best decision, however, was marrying his high school sweetheart, Bonnie. Their marriage produced a son, Kyle, and a daughter, Kim.

While immersed in mechanics, Terry also had an interest in space. After graduation, he went to work at Lockheed Missiles and Space Co. in Sunnyvale, CA, and enrolled at Stanford University part time. At Lockheed, his assignments included the dynamic analysis of separation systems such as Agena-booster and spacecraft-Agena. During this time he developed, along with courses at Stanford from Professor Tom Kane, a love for dynamics. After several years, he completed a Masters of Science degree from Stanford and due to family reasons, moved to Huntsville, AL, with Lockheed. After a year in Huntsville, Terry got the itch to continue his graduate education. While visiting his undergraduate alma mater in August 1965, the department head, Professor Dan Pletta, offered him a fellowship, and he went back to graduate school one month later. (Department heads could do things like that in those days.) Two years later, Terry left with a PhD and received a faculty position offer from Cornell University in the Theoretical and Applied Mechanics Department, where he spent the next six years.

Terry moved to the Naval Research Laboratory in 1974 after one year at NASA Goddard Space Flight Center on a NRC post-doctoral position. At NRL and NASA, he delved into orbit theories, Hamiltonian mechanics, and Lie Series. He made at least two good decisions at NRL: he hired Shannon Coffey and Bob Lindberg. In addition to Shannon and Bob, he had fun working with Bernie Kaufman, Landis Markley, and Bob Dasenbrock. In 1981, Terry was awarded the Navy Meritorious Service Medal. He left NRL in 1983 and spent two years at the CIA. This period with the CIA will not be discussed further except to say that the fun with space continued. Terry then received an offer from Jim Roth and Chuck Perkins at General Research Corp. (GRC) to open and develop an office in the Washington, DC, area. He accepted the challenge and remained there until 1994. At GRC he continued to have fun and developed relationships with some whom he still works with occasionally, including Felix Hoots, who joined GRC to run the Colorado Springs office shortly after Terry stood up the DC office. During this phase of his career, Terry served as editor for the International Journal of Celestial Mechanics (he remains an associate editor through the publishing of these proceedings), Journal of Guidance, Control, and Dynamics, and the Journal of the Astronautical Sciences. Terry was honored by the American Astronautical Society with the Dirk Brouwer Award in 1989.

In 1994, Terry accepted a Visiting Professor position at the Naval Postgraduate School. So he and Bonnie pack up and move to the Monterey area and bought a house in Pebble Beach before the housing prices skyrocketed. There he met Mike Ross, with whom he continues to work on research projects. In 1997, Terry received an offer to be the Department Head of the Aerospace Engineering Department at Texas A&M University. He saw the significant potential of the department, and being competitive and liking challenges, he accepted the offer. His insight into the department's potential was correct, and the department's reputation began to rise. As the department continued to expand, its national ranking moved up to about 10th. While at A&M, Terry, Srinivas Vadali, and John Junkins won one of the three AFOSR TechSat21 grants; their research into the dynamics and control of satellite formations began and continues through the publishing of these proceedings. In 2010, Terry, Srinivas, and others, published a book entitled, *Spacecraft Formation Flying: Dynamics, Control and Navigation*. The AIAA honored Terry with the Mechanics and Control of Flight Award in 1998. He was also elected to the International Academy of Astronautics in 1998, the National Academy of Engineering in 1999, and the European Academy of Sciences in 2002.

Terry stepped down from the Department Head job at the end of 2001 to conduct research full time and return to his home in Pebble Beach. The quality of his work remained exceptional as evidenced by twice receiving Best Paper awards at AAS Space Flight Mechanics conferences. In 2002, he began working with Chris Sabol and Kim Luu, who had recently transferred to the Air Force Maui Optical and Supercomputing (AMOS) site to develop an astrodynamics capability in support of the facility mission. Terry now spends 3-4 months of the year at AMOS. During this phase of his career, Terry also became the US Technical Chair for the US-Russia Space Surveillance Workshop series, working along with General Chair Ken Seidelmann to hold workshops in 2000, 2003, 2005, 2007, 2010, with another planned for 2012. As a result of these and other efforts, Terry and his collaborators received the AAAS International Scientific Cooperation Award in 2005. Terry and Ken also arranged the first US-China Space Surveillance Technical Interchange in 2009.

Terry has published over 200 conference papers and journal articles and is coauthor on several more in these proceedings. He has no immediate plans to retire; as Terry puts it, "*Why retire when you can work with excellent people on fun research projects in Pebble Beach and Maui?*"

PREFACE

"I trust my equations more than I trust your computer" – Terry Alfriend

At first, the quote may come across as presumptuous but if you know the man, you realize it's not presumptuous at all. In fact, that quote embodies a philosophy that all young scientist and engineers should hear: if you can use mathematical relationships to describe a system, then you can explain its behavior and can be said to understand the system. Dr. Kyle T. (Terry) Alfriend has a special gift for breaking complex dynamical problems down to their purest form and using equations to garner understanding and physical insight.

For more than forty years, Terry Alfriend has been making key contributions to our understanding of the flight mechanics and control of space vehicles. His career includes an unusually rich mix of experience in academia, industry and government. His innovations appear prominently in subjects as diverse as analytical celestial mechanics, satellite formation flying, attitude dynamics and control, surveillance of space, probabilistic problems in astrodynamics including probability-of-collision formulations used by NASA to ensure safety of manned space flight, and application of space systems to intelligence, surveillance and reconnaissance. It is remarkable that papers from every phase of his career continue to be cited regularly at conferences and in journals.

This volume of the Advances in the Astronautical Sciences contains papers presented at the AAS Alfriend Astrodynamics Symposium held 17-19 May 2010 at the Monterey Plaza Hotel to honor Dr. Alfriend. The symposium organizers would like to thank all of the authors and participants for making it an outstanding event, the AAS Space Flight Mechanics Committee for providing use of the conference management system, and to Univelt for publishing the proceedings. We would also like to thank Bonnie Alfriend for too many things to mention.

Most importantly, these proceedings are for those of us following in Terry's footsteps. Terry is truly a leader in our field and the contents of this volume provide insight into the depth and breadth of his expertise and influence. The understanding one obtains from Terry's approach is far greater than what is possible through pure computer simulation. "This is what the simulation gave me" is never an acceptable answer to "Why?"

Terry, we honor you, thank you, and look forward to several more decades of contributions.

Shannon Coffey
John Junkins
Kim Luu
Mike Ross
Chris Sabol
Paul Schumacher

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TECHNICAL SESSION 1

SESSION 1

Chair: Dr. Shannon Coffey
Naval Research Laboratory

Introductory Remarks: Prof. John Junkins
Texas A&M University

The following paper was not available for publication:

AAS 10-306
(Paper Withdrawn)

AAS 10-301

RESONANCES AND THE STABILITY OF STATIONARY POINTS

A. Elipe,* V. Lanchares† and A. I. Pascual‡

The question of Lyapunov stability of stationary points around a central body has been studied in absence of resonances and in the case of resonances of order 3 and 4, by means of the computation of the normal form up to second order. However, some special degenerate cases are not covered, as it happens for resonances of order 5 and 6, when the free parameters of the problem are chosen properly. In this paper we deal with these resonances and apply appropriate results to establish the stability properties of the stationary points. [View Full Paper]

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AAS 10-302

ON ROTO-TRANSLATORY MOTION, REDUCTIONS AND RADIAL INTERMEDIARIES

Sebastián Ferrer* and Martin Lara†

The roto-translational dynamics of an axial-symmetric rigid body is discussed in a central gravitational field. The six-degree of freedom Hamiltonian problem is formulated as a perturbation of the Kepler motion and torque-free rotation in which we limit to the MacCullagh term. A chain of canonical transformations is used to reduce the problem. First, the elimination of the nodes reduces the problem to a system of four degrees of freedom. Then, the elimination of the parallax simplifies the resulting Hamiltonian, which is shaped as a radial intermediary plus a remainder. Some features of this integrable intermediary are pointed out. The normalized first order system in closed form is also given, thus completing the solution. Finally the full reduction of the radial intermediary is constructed using the Hamilton-Jacobi equation. [View Full Paper]

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MEASUREMENT MODEL NONLINEARITY IN ESTIMATION OF DYNAMICAL SYSTEMS*

Manoranjan Majji,† John L. Junkins‡ and J. D. Turner**

Role of nonlinearity of the measurement model and its interactions with quality of measurements and geometry of the problem is coarsely examined. It is shown that for problems in astrodynamics several important conclusions can be drawn by an examination of the transformations of density function in various coordinate systems and choices of variables. Probability density transformations through nonlinear, smooth and analytic functions are examined and the role of change of variables in calculus of random variables is elucidated. It is shown that the transformation of probability density functions through mappings provides insight in to problems, a priori providing the analyst with an insight on the interaction of nonlinearity, uncertainty and geometry of estimation problems. Examples are presented to highlight salient aspects of the discussion. Finally, a sequential orbit determination problem is analyzed and the transformation formula is shown to be helpful in making the choice of coordinates for estimation of dynamic systems. [View Full Paper]

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* Dedicated to Professor Kyle T. Alfriend for his contributions to astronautics.

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AAS 10-304

APPLICATIONS OF SYMPLECTIC TOPOLOGY TO ORBIT UNCERTAINTY AND SPACECRAFT NAVIGATION

Daniel J. Scheeres* and Maurice A. de Gosson†

Gromov's symplectic non-squeezing theorem, a fundamental property from symplectic topology, is applied to the study of uncertainty analysis in Hamiltonian Dynamical systems with a particular emphasis on spacecraft trajectory uncertainty. Previous results published in the literature are re-derived and shown to be similar to the uncertainty principle of quantum mechanics. The application of Gromov's Theorem to uncertainty distributions in Hamiltonian Dynamical systems are discussed, including the effect of time mapping and measurement updates. Finally, we provide constraint relations on the phase volume of a distribution and the Gromov width.

Keywords: symplectic capacity, uncertainty principle, Hamiltonian systems.

[View Full Paper]

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† Financed by the Austrian Research Agency FWF (Projektnummer P20442-N13). Universität Wien, NuHAG, Fakultät für Mathematik, A-1090 Vienna, Austria.

AAS 10-305

CONTROL OF THE RESTRICTED THREE-BODY PROBLEM

Tamás Kalmár-Nagy[*] and Daniele Mortari[†]

The N = 3 body problem is a 9-DOF Hamiltonian system, but using the first integrals it can be reduced to 4 degrees of freedom. A simpler, well-studied case is the circular restricted three-body problem (CRTBP). In this problem two bodies of a finite mass revolve around their center of mass and a third body of negligible mass moves in their gravitational field without exerting any influence on the motion of the two other bodies. Since the orbits of the two finite mass bodies conform to the known solution of the two-body case, the problem is reduced to the study of the motion of the particle in the field of the two co-orbiting primaries... [View Full Paper]

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AAS 10-307

ESTIMATING DENSITY USING PRECISION SATELLITE ORBITS FROM MULTIPLE SATELLITES

Craig A. McLaughlin,* Travis Lechtenberg† and Eric Fattig†

This paper examines atmospheric densities estimated using precision orbit ephemerides (POE) from several satellites including CHAMP, GRACE, and TerraSAR-X. The results of the calibration of CHAMP and GRACE-A densities derived using POEs with those derived using accelerometers are compared for various levels of solar and geomagnetic activity to examine the consistency in calibration between the two satellites. Densities from CHAMP and GRACE are compared when GRACE is orbiting nearly directly above CHAMP. In addition, the densities derived simultaneously from CHAMP, GRACE-A, and TerraSAR-X are compared to the Jacchia 71 model densities to observe altitude effects and consistency in the offsets from Jacchia 71 among all three satellites. [View Full Paper]

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TECHNICAL SESSION 2

SESSION 2

Chair: Dr. Chris Sabol
Air Force Research Laboratory

AAS 10-308

EARTH-IMPACT MODELING AND ANALYSIS OF A NEAR-EARTH OBJECT FRAGMENTED AND DISPERSED BY NUCLEAR SUBSURFACE EXPLOSIONS*

Bong Wie† and David Dearborn‡

This paper describes the orbital dispersion modeling, analysis, and simulation of a near-Earth object (NEO) fragmented and dispersed by nuclear subsurface explosions. It is shown that various fundamental approaches of Keplerian orbital dynamics can be effectively employed for the orbital dispersion analysis of fragmented NEOs. The nuclear subsurface explosion is the most powerful method for mitigating the impact threat of hazardous NEOs although a standoff explosion is often considered as the preferred approach among the nuclear options. In addition to non-technical concerns for using nuclear explosives in space, a common concern for such a powerful nuclear option is the risk that the deflection mission could result in fragmentation of the NEO, which could substantially increase the damage upon its Earth impact. However, this paper shows that under certain conditions, proper disruption (i.e., fragmentation and large dispersion) using a nuclear subsurface explosion, even with shallow burial (< 5 m), is a feasible strategy providing considerable impact damage reduction if all other approaches failed.
[View Full Paper]

* This paper was published previously as AAS 10-137, in *Spaceflight Mechanics 2010*, Daniele Mortari et al., Editors, (San Diego, California: Published for the American Astronautical Society by Univelt, Inc., 2010), *Advances in the Astronautical Sciences*, Vol. 136-I, 2010, pp. 567–586 (paper presented at the 20th AAS/AIAA Space Flight Mechanics Meeting, San Diego, California, Feb. 15-17, 2010).

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SATELLITE BREAKUP PARAMETER DETERMINATION

Felix Hoots* **and Marlon Sorge†**

A satellite breakup can cause collision risk to other resident satellites. If the time, location, and energy content of the breakup can be determined, The Aerospace Corporation has models that can quickly estimate the risk to other resident satellites from the debris. We have developed a method that allows determination of all required breakup parameters within about 12 hours after the breakup event. If a large number of radar tracks are available, this timeline could be even shorter. The method then facilitates rapid determination of debris collision risk to resident satellites, providing satellite operators with timely space situational awareness. [View Full Paper]

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DESIGN OF SATELLITE FORMATIONS IN ORBITS OF HIGH ECCENTRICITY WITH PERFORMANCE CONSTRAINTS SPECIFIED OVER A REGION OF INTEREST

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

The Magnetospheric Multiscale (MMS) mission requires a formation of four satellites in a nearly regular tetrahedron throughout a Region of Interest (RoI), defined near the apogee of a highly eccentric reference orbit. In this paper, an approach for determining the differential mean orbital element initial conditions for formations in highly eccentric orbits to maximize a Quality Factor (QF) in a RoI is presented. Previous works on the design of formations in high-eccentricity orbits have used numerical integration-based approaches for orbit propagation. We present a fast optimization scheme by using the Gim-Alfriend state transition matrix. Two optimization approaches are presented for the long-term MMS formation design: a single-orbit constrained (SOC) optimization, subject to an along-track drift condition, and a multi-orbit unconstrained (MOU) optimization. A new along-track drift condition is proposed to minimize the along-track drift only in certain portions of the orbit and is shown to produce much more stable long-term behaviour of the QF than the previous condition. A verification of our results using the NASA General Mission Analysis Tool is provided. Under ideal conditions, i.e., without errors in the establishment of the initial conditions, the best formation can satisfy the MMS mission QF requirements for over 80 days without corrective action. [View Full Paper]

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AAS 10-311

GEOSYNCHRONOUS LARGE DEBRIS REORBITER: CHALLENGES AND PROSPECTS

Hanspeter Schaub* **and Daniel F. Moorer Jr.†**

An elegant solution is proposed to an old problem of how to remove expired or malfunctioning satellites from the geosynchronous belt. Previous "space-tug" concepts describe a scenario where one craft (the tug) docks with another (debris) and then boosts that object to a super-synchronous orbit. The most challenging aspect of these concepts is the very complex proximity operations to an aging, possibly rotating and, probably, non-cooperative satellite. Instead, the proposed method uses an elegant blend of electrostatic charge control and low-thrust propulsion to avoid any contact requirement. The Geosynchronous Large Debris Reorbiter (GLiDeR) uses active charge emission to raise its own absolute potential to 10's of kilovolts and, in addition, directs a stream of charged particles at the debris to increase its absolute potential. In a puller configuration the opposite polarity of the debris creates an attractive force between the GLiDeR and the debris. Pusher configurations are feasible as well. Next, fuel-efficient micro-thrusters are employed to gently move the reorbiter relative to the debris, and then accelerate the debris out of its geosynchronous slot and deposit it in a disposal orbit. Preliminary analysis shows that a 1000kg debris object can be re-orbited over 2-4 months. During the reorbit phase the separation distance is held nominally fixed without physical contact, even if the debris is tumbling, by actively controlling the charge transfer between the reorbiter and the debris. Numerical simulations are presented illustrating the expected performance, taking into account also the solar radiation pressure.
[View Full Paper]

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AAS 10-312

FEEDBACK CONTROL FOR FORMATION FLYING MAINTENANCE USING STATE TRANSITION MATRIX

Hui Yan* and Qi Gong†

The Linear Quadratic Regulator (LQR) control design method has been widely used for satellite formation maintenance. In this paper a new feedback control is proposed to solve LQR problems using state transition matrix. Such a method has the potential to reduce the online computational burden. We apply the control law to formation flying maintenance under J_2 perturbation using the Gim-Alfriend state transition matrix. The numerical simulations demonstrate the STM feedback control via receding horizon scheme works well. The projected circular orbits are maintained very well for the circular and elliptic Chief orbits after 100 days propagation under J_2 influence. Much control effort is needed to track the projected circular orbits if the Chief orbit is elliptic. [View Full Paper]

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OPTIMAL CONTROL OF RELATIVE MOTION IN ARBITRARY FIELDS: APPLICATION AT DEIMOS

Ryan P. Russell* **and Gregory Lantoine†**

We formulate a second-order, general dynamics, relative motion framework to solve for optimal finite burn transfers in complex gravity fields that are not amenable to analytic solutions. The second-order variational equations are employed in a Cartesian frame that is general in fidelity and simple to implement. For a passive chief orbit we show that only 16 coefficient functions are necessary to accommodate most dynamical environments of interest. We pre-compute and curve-fit the coefficient functions which represent the time-varying Jacobians and Hessians of the state equations evaluated along the chief orbit. Once the coefficient functions are evaluated, the resulting CUrve-fit quadRatic Variational Equations (*CURVE*) model is almost transparent to the fidelity level and therefore is well suited for the repeated iterations required by nonlinear optimization. The optimal control problem is solved using a robust, second order technique that is a variant of differential dynamic programming. The model and optimal rendezvous problems are demonstrated in the highly perturbed dynamical environment of the Martian moon Deimos. The resulting implementation is useful for any relative motion application requiring optimal targeting, particularly in the context of complex force fields. While intended primarily for exotic destinations such as the Moon, asteroids, comets, and planetary satellites; the *CURVE* model and optimal control framework can also be useful for Earth orbiters, especially in cases of large eccentricity and large geopotentials. [View Full Paper]

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AAS 10-314

ELLIPTIC RENDEZVOUS IN THE CHASER SATELLITE FRAME

Prasenjit Sengupta*

The analysis of satellite rendezvous in planetary orbits typically derives control laws in a frame rotating with the target satellite. However, since the control law is ultimately required in the chaser satellite's frame, knowledge of the chaser satellite's motion with respect to the planet may be required to correctly transform the control laws. The transformation may also result in sub-optimal or infeasible control laws. This paper analyzes the rendezvous problem in the chaser satellite's frame directly. A nonlinear transformation between the chaser and target frames, in terms of relative position and velocity variables is derived. This is used to formulate and solve the rendezvous problem using optimal power-limited propulsion analytically, that includes nonlinear effects. A framework is thus developed, that can be used to solve the orbital transfer problem. The efficacy of the derived control algorithm is demonstrated by means of an example.
[View Full Paper]

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OPTIMAL MULTI-IMPULSE ORBIT TRANSFER USING NONLINEAR RELATIVE MOTION DYNAMICS

Weijun Huang*

Satellite formation resizing and reconfiguration can be reduced as the optimization problem of transferring a satellite from one formation to another. In this paper, a hybrid method of using the primer vector is proposed for solving this problem. In this method, the nonlinear calculus of variation (COV) based primer vector optimization is incorporated with the linear algebra based primer vector optimization, in which the linear solution can be regarded as initial guess for the nonlinear COV based optimization. Numerical test shows that this hybrid method is extremely fast and accurate. [View Full Paper]

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TECHNICAL SESSION 3

SESSION 3

Chair: Dr. Paul Schumacher
Air Force Research Laboratory

SPACE SURVEILLANCE – U.S., RUSSIA AND CHINA

P. K. Seidelmann*

With the launch of Sputnik the U.S. and Russia began the process of tracking artificial satellites. This led to developments for observations, orbit determination, and catalog maintenance. The two countries followed somewhat different approaches to the same problem based on the available hardware and theoretical developments. As more sophisticated hardware and theories have been developed, progress has been made. However, new problems have developed due to debris, collision possibilities, and reentering objects. Also, the range of spacecraft has increased to include geosynchronous orbits. In more recent times the European Space Agency (ESA) and China have become involved in various aspects of Space Surveillance.

In 1994 the first meeting between U.S. and Russian experts in the field of space surveillance was held. Since then, seven more U.S.–Russia Space Surveillance Workshops have been held, with the addition of participants from ESA. Terry Alfriend has been the U.S. Technical Chairman for many of these workshops. In 2009 a U.S.–China Space Surveillance Technical Interchange was held in Shanghai, China, and Terry was the U.S. Technical Chairman. [View Full Paper]

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AAS 10-317

SEQUENTIAL PROBABILITY RATIO TEST FOR COLLISION AVOIDANCE MANEUVER DECISIONS

J. Russell Carpenter* and F. Landis Markley†

When facing a conjunction between space objects, decision makers must choose whether to maneuver for collision avoidance or not. We apply a well-known decision procedure, the sequential probability ratio test, to this problem. We propose two approaches to the problem solution, one based on a frequentist method, and the other on a Bayesian method. The frequentist method does not require any prior knowledge concerning the conjunction, while the Bayesian method assumes knowledge of prior probability densities. Our results show that both methods achieve desired missed detection rates, but the frequentist method's false alarm performance is inferior to the Bayesian method's. [View Full Paper]

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AAS 10-318

COMPARISON OF COVARIANCE-BASED TRACK ASSOCIATION APPROACHES WITH SIMULATED RADAR DATA

Keric Hill,[*] Chris Sabol[†] and Kyle T. Alfriend[‡]

When the Air Force Space Surveillance Network observes an object that does not correlate to an entry in the Space Object Catalog, it is called an Uncorrelated Track (UCT). Some of these UCTs arise from objects that are not in the Space Catalog. Before a new object can be added to the catalog, three or four UCTs must be associated so that a meaningful state can be estimated. Covariance matrices can be used to associate the UCTs in a more statistically valid and automated manner than the current labor-intensive process, however the choice of parameters used to represent the orbit state have a large impact on the results. Covariance-based track association was performed in 10-day simulations of 1000 space objects within a 20-km band of semimajor axis using many different orbit parameters and propagation methods and compared to a fixed position gate association method. It was found that Cartesian covariance with linearized propagation performed poorly, but when propagated with the Unscented Transform the results were much better. Elliptical curvilinear coordinates also performed well, as did covariance in osculating equinoctial elements propagated with the Unscented Transform, but a covariance in mean equinoctial elements propagated with the Unscented Transform achieved the best results. [View Full Paper]

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CORRELATION OF OPTICAL OBSERVATIONS OF EARTH-ORBITING OBJECTS BY MEANS OF PROBABILITY DISTRIBUTIONS

K. Fujimoto* and D. J. Scheeres†

Situational awareness of Earth-orbiting particles is highly important for future human activities in space. For optical observations of debris, multiple observations must be combined in order to determine the orbit of the observed object. It is generally uncertain, however, whether two arbitrary tracks are of the same object, and solving this problem can be computationally intensive. In this paper, we propose a technique of correlating multiple optical observations by means of probability distributions in Poincaré orbit element space. These distributions are mapped linearly in order to reduce computational burden but without significantly losing accuracy. [View Full Paper]

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AAS 10-320

COMPARISON OF SIGMA-POINT AND EXTENDED KALMAN FILTERS ON A REALISTIC ORBIT DETERMINATION SCENARIO

John Gaebler,[*] Sun Hur-Diaz[†] and Russell Carpenter[*]

Sigma-point filters have received a lot of attention in recent years as a better alternative to extended Kalman filters for highly nonlinear problems. In this paper, we compare the performance of the additive divided difference sigma-point filter to the extended Kalman filter when applied to orbit determination of a realistic operational scenario based on the Interstellar Boundary Explorer mission. For the scenario studied, both filters provided equivalent results. The performance of each is discussed in detail.
[View Full Paper]

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AAS 10-321

ADAPTIVE GAUSSIAN SUM FILTERS FOR SPACE SURVEILLANCE TRACKING

Joshua T. Horwood, Nathan D. Aragon and Aubrey B. Poore[*]

While orbital propagators have been investigated extensively over the last fifty years, the consistent propagation of state covariances and more general (non-Gaussian) probability densities has received relatively little attention. The representation of state uncertainty by a Gaussian mixture is well-suited for problems in space situational awareness. Advantages of this approach which are demonstrated in this paper include the potential for long-term propagation in data-starved environments, the capturing of higher-order statistics and more accurate representation of nonlinear dynamical models, the ability to make the filter adaptive using realtime metrics, and parallelizability. Case studies are presented establishing uncertainty consistency and the effectiveness of the proposed adaptive Gaussian sum filter. [View Full Paper]

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AAS 10-322

MODIFIED CHEBYSHEV-PICARD ITERATION METHODS FOR SOLUTION OF INITIAL VALUE PROBLEMS

Xiaoli Bai[*] and John L. Junkins[†]

The solution of initial value problems provide the state history for a given dynamic system, for prescribed initial conditions. Existing methods for solving these problems have not been very successful in exploiting parallel computation architectures, mainly because most of the integration methods implemented on parallel machines are only modified versions of forward integration approaches, which are typically poorly suited for parallel computation. This paper propose parallel-structured modified Chebyshev-Picard iteration (MCPI) methods, which iteratively refine estimates of the solutions until the iteration converges. Using Chebyshev polynomials as the orthogonal approximation basis, it is straightforward to distribute the computation of force functions and polynomial coefficients to different processors. A vector-matrix form is introduced that makes the methods computationally efficient. The power of the methods is illustrated through satellite motion propagation problems. Compared with a Runge-Kutta 4-5 forward integration method implemented in MATLAB, the proposed methods generate solutions with improved accuracy as well as several orders of magnitude speedup, even prior to parallel implementation. Allowing to only integrate position states or perturbation motion achieve further speedup. Parallel realization of the methods is implemented using a graphics processing unit to provide an inexpensive parallel computation architecture. Significant further speedup is achieved from the parallel implementation.
[View Full Paper]

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LS GEO IOD

James R Wright*

I have constructed and demonstrated a new fast-running algorithm to perform refined orbit determination for any spacecraft in GEO (geosynchronous earth orbit), without *user* requirement for an a priori orbit estimate. We now have a *refined* method for GEO initial orbit determination (IOD). This is enabled by the use of equinoctial orbit elements, by a one-dimensional search in the equinoctial orbit element *mean argument of orbit longitude*, by the use of sensor locations to reduce the one-dimensional search, and by convergence boundaries of the nonlinear least squares (LS) algorithm. I shall refer herein to the new algorithm as LS_GEO_IOD. Algorithm LS_GEO_IOD employs any desired perturbative acceleration model for numerical trajectory integration, and its success appears to be independent of input measurement type. [View Full Paper]

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TECHNICAL SESSION 4

SESSION 4

Chair: Prof. John Junkins
Texas A&M University

The following papers were not available for publication:

AAS 10-326
(Paper Withdrawn)

AAS 10-329
(Paper Withdrawn)

AAS 10-324

FURTHER STUDIES ON SINGULAR VALUE METHOD FOR STAR PATTERN RECOGNITION AND ATTITUDE DETERMINATION

Jer-Nan Juang* and Yu-Chi Wang†

The objective of this paper is to study the effectiveness of a star pattern recognition method using singular value decomposition of a measured unit column vector matrix in a measurement frame and the corresponding catalog vector matrix in a reference frame. The approach is to use sensitivity analysis to define an effectiveness measure for a pairing process for individual measured and cataloged stars. The sensitivity of singular values relative to separation angle of star vectors will be studied to establish their correlation. A new method is proposed to generate the mission catalog to improve the quality of pattern recognition in speed and accuracy. [View Full Paper]

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COVARIANCE-BASED SCHEDULING OF A NETWORK OF OPTICAL SENSORS

Keric Hill,* Paul Sydney,* Kris Hamada,* Randy Cortez,*
K. Kim Luu,† Paul W. Schumacher, Jr.† and Moriba Jah†

Maintaining the catalog of Resident Space Objects (RSOs) is vitally important to the protection of space assets. However, currently the Space Surveillance Network tasking for deep space RSOs is based upon an ad hoc RSO priority system and only crudely accounts for the actual error in the catalog orbit estimates. Previous work showed that significant improvements in the median catalog accuracy were achieved using a scheduler that computed the effectiveness of future observations in reducing catalog error using the predicted observation geometry, measurement noise, and orbit error covariance. A high-fidelity simulation environment of networked optical sensors called TASMAN (Tasking Autonomous Sensors in a Multiple Application Network) was used as a flexible test-bed for evaluating this covariance-based mission planning algorithm. With the added complexity of sensor outages due to weather or other causes, simulations were performed that show the covariance-based scheduling algorithm offers significant potential for improving overall catalog accuracy. [View Full Paper]

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AAS 10-327

TWO IMPULSE REORIENTATION OF SPINNING AXISYMMETRIC BODY: SINGLE AXIS THRUST

Neha Satak,* Jeremy J. Davis,* James Doebbler* and John E. Hurtado†

A sequence of two impulses can be used to redirect the spin axis of an axi-symmetric rigid body. The first impulse initiates coning motion by imparting an initial transverse component of angular velocity. The second impulse brings the coning motion to a halt by making the transverse angular velocity zero. When the thrust axis is fixed along one axis in the transverse plane then a two impulse maneuver can be designed with a coast time before the initiation of the two impulse maneuver. The coast time is required to point the thrust axis in specific direction for a two impulse solution. Further, by appropriately choosing the time of the second impulse, a solution is found for bodies with a thrust restricted to only one direction along that axis. [View Full Paper]

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AAS 10-328

NONLINEAR SYSTEM IDENTIFICATION: A CONTINUOUS-TIME BILINEAR STATE SPACE APPROACH

Cheh-Han Lee* and Jer-Nan Juang†

A class of nonlinear systems can be approximated by a bilinear system to an arbitrary high order as needed. In this paper, we develop an improved method using single experiment with multiple pulses for bilinear system identification. The main objective of this improved method is to identify a nonlinear system. Numerical examples such as the Euler's equation describing the rotation of a rigid body are given to demonstrate the power of the bilinear approach for nonlinear system identification. [View Full Paper]

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AAS 10-330

A SUPERSPACE METHOD FOR DISCRETE-TIME BILINEAR MODEL IDENTIFICATION BY INTERACTION MATRICES

Minh Q. Phan[*] and Haris Čelik[†]

This paper presents a method for discrete-time bilinear state-space model identification from a single set of input-output data. The initial state can be unknown. By extending the interaction matrix formulation from linear to bilinear state-space models, the bilinear system state is expressed in terms of input-output measurements. This relationship is used to convert the bilinear model to an Equivalent Linear Model (ELM) which can be identified by any linear identification method such as a superspace method presented here. The bilinear state-space model is then extracted from the identified ELM. A companion paper deals with the identification of input-output models instead of state-space models for a bilinear system using the same interaction matrix approach.
[View Full Paper]

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THE INFLUENCE ON STABILITY ROBUSTNESS OF COMPROMISING ON THE ZERO TRACKING ERROR REQUIREMENT IN REPETITIVE CONTROL

Yunde Shi* and Richard W. Longman†

Repetitive control (RC) can be used to design active vibration isolation mounts that aim to cancel the influence of spacecraft vibrations on fine pointing equipment. It can cancel the influence of slight imbalance in momentum wheels, reaction wheels, and CMGs. Since RC aims for zero error, it requires reasonably accurate knowledge of the system dynamics all the way to Nyquist frequency. As a result special methods are needed to establish robustness to model error. A series of publications have demonstrated a method of averaging a cost function over models to increase the robustness. A previous paper improves on this by adjusting the learning rate as a function of frequency to further improve robustness, but there is still a hard limit on phase error. This paper considers yet one more approach, and all three can be used simultaneously. Here we compromise on the zero tracking error requirement for frequencies that require extra robustness. This allows one to extend this hard limit making a RC tolerate larger model errors. A quadratic cost is used that penalizes not just the rate of change of the input function, but also the size of the input function. We first establish how to do this for the sister field of iterative learning control, and then the frequency response characteristics are produced for design of repetitive control. The method can improve tracking error for a frequency interval above the frequency at which one would otherwise have to cut off the learning due to model error. Model uncertainty can be used directly in the design process to produce stable RC laws for any level of uncertainty. The design approach differs from typical earlier work that used a sharp frequency cutoff, and instead uses a minimal amount of attenuation needed to produce stability. [View Full Paper]

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GENERALIZED FREQUENCY DOMAIN STATE-SPACE MODELS FOR ANALYZING FLEXIBLE ROTATING SPACECRAFT

James D. Turner[*] and Tarek Elgohary[†]

The mathematical model for a flexible spacecraft that is rotating about a single axis rotation is described by coupled rigid and flexible body degrees-of-freedom, where the equations of motion are modeled by integro-partial differential equations. Beam-like structures are often useful for analyzing boom-like flexible appendages. The equations of motion are analyzed by introducing generalized Fourier series for the deformational coordinate that transforms the governing equations into a system of ordinary differential equations. Though technically straightforward, two problems arise with this approach: (1) the model is frequency-truncated because a finite number of series terms are retained in the model, and (2) computationally intense matrix-valued transfer function calculations are required for understanding the frequency domain behavior of the system. Both of these problems are resolved by: (1) computing the Laplace transform of the governing integro-partial differential equation of motion; and (2) introducing a generalized state space (consisting of the deformational coordinate and three spatial partial derivatives, as well as single and double spatial integrals of the deformational coordinate). The Laplace domain equation of motion is cast in the form of a linear state-space differential equation that is solved in terms of a matrix exponential and convolution integral. The structural boundary conditions defined by Hamilton's principle are enforced on the closed-form solution for the generalized state space. The generalized state space model is then manipulated to provide analytic scalar transfer function models for the original integro-partial differential system dynamics. Symbolic methods are used to obtain closed-form Eigen decomposition–based solutions for the matrix exponential/convolution integral algorithm. Numerical results are presented that compare the classical series based approach with the generalized state space approach for computing representative spacecraft transfer function models. [View Full Paper]

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