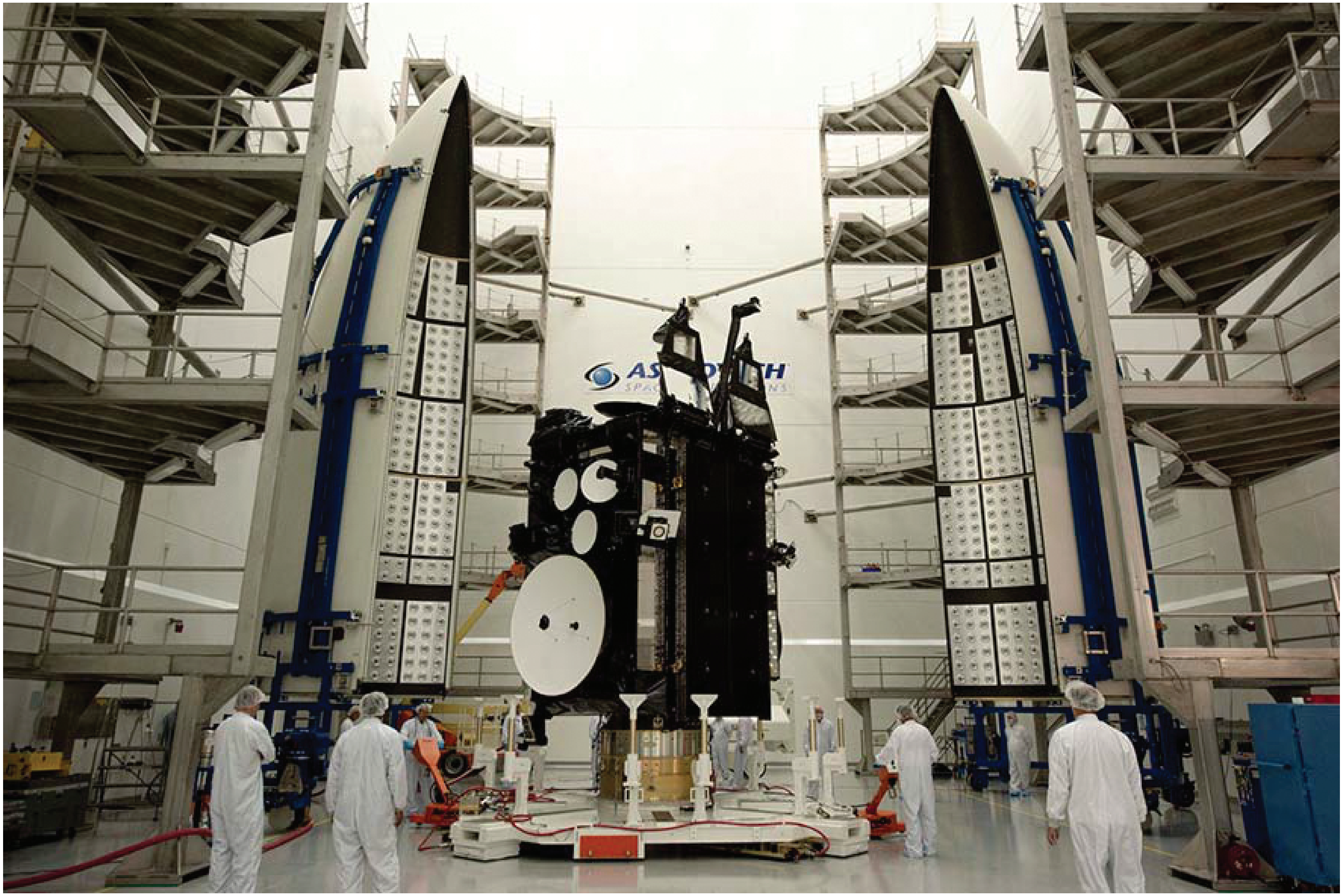
GUIDANCE, NAVIGATION, AND CONTROL 2018

Front Cover Photo:

The Orion structural test article short stack, consisting of the service module and crew module, are being prepared for a model vibration test in a test chamber at Lockheed Martin near Denver. The structural test articles are structural twins of the flight Orion and are used to perform various test to how the structures will perform during launch, flight and landing. Photo Credit: Lockheed Martin.

Frontispiece Photo:

The Air Force's second Advanced Extremely High Frequency (AEHF-2) satellite is encapsulated inside a 5-meter-diameter payload fairing in preparation for launch on a United Launch Alliance Atlas V rocket from Space Launch Complex-41 at Cape Canaveral Air Force Station. Photo Credit: United Launch Alliance.



GUIDANCE, NAVIGATION, AND CONTROL 2018

Volume 164
ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Cheryl A. H. Walker

Proceedings of the 41st Annual AAS Rocky Mountain Section Guidance and Control Conference held February 1–7, 2018, Breckenridge, Colorado.

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 2018

Library of Congress Card No. 57-43769

ISSN 0065-3438

ISBN 978-0-87703-649-4 (Hard Cover Plus CD ROM)
ISBN 978-0-87703-650-0 (Digital Version)

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

HISTORICAL SUMMARY

The annual American Astronautical Society Rocky Mountain Guidance, Navigation and Control Conference began as an informal exchange of ideas and reports of achievements among local guidance and control specialists. Since most area guidance and control experts participate in the American Astronautical Society, it was natural to gather under the auspices of the Rocky Mountain Section of the AAS.

In the late seventies, Bud Gates, Don Parsons and Sherm Seltzer jointly came up with the idea of convening a broad spectrum of experts in the field for a fertile exchange of aerospace control ideas. At about this same time, Dan DeBra and Lou Herman had discussed a similar plan.

Bud and Don approached the AAS Section Chair, Bob Culp, with their proposal. In 1977, Bud Gates, Don Parsons, and Bob Culp organized the first conference, and began the annual series of meetings the following winter. Dan and Lou were delighted to see their concept brought to reality and joined enthusiastically from afar. In March 1978, the First Annual Rocky Mountain Guidance and Control Conference met at Keystone, Colorado. It met there for eighteen years, moving to Breckenridge in 1996 where it has been for more than 20 years. The 2018 Conference was the 41th Annual AAS Rocky Mountain Guidance, Navigation and Control Conference.

There were thirteen members of the original founders. The first Conference Chair was Bud Gates, the Co-Chair was Section Chair Bob Culp, with the arrangements with Keystone by Don Parsons. The local session chairs were Bob Barsocchi, Carl Henrikson, and Lou Morine. National session chairs were Sherm Seltzer, Pete Kurzhals, Ken Russ, and Lou Herman. The other members of the original organizing committee were Ed Euler, Joe Spencer, and Tom Spencer. Dan DeBra gave the first tutorial.

The style was established at the first Conference, strictly adhered to until 2013, involved no parallel sessions and two three-hour technical/tutorial sessions. For the first fifteen Conferences, the weekend was filled with a tutorial from a distinguished researcher from academia. The Conferences developed a reputation for concentrated, productive work.

After the 2012 conference, it was clear that overall industry budget cuts were leading to reduced attendance and support. In an effort to meet the needs of the constituents, parallel conference sessions were added for 3 of the 8 sessions on a trial basis during the 2013 conference. The success of the parallel sessions was carried forward and expanded.

A tradition from the beginning and retained until 2014 had been the Conference banquet. A general interest speaker was a popular feature. The banquet speakers included:

Banquet Speakers

1978 Sherm Seltzer, NASA MSFC, told a joke
1979 Sherm Seltzer, Control Dynamics, told another joke
1980 Andrew J. Stofan, NASA Headquarters, "Recent Discoveries through Planetary Exploration."
1981 Jerry Waldvogel, Cornell University, "Mysteries of Animal Navigation."
1982 Robert Crippen, NASA Astronaut, "Flying the Space Shuttle."
1983 James E. Oberg, author, "Sleuthing the Soviet Space Program."
1984 W. J. Boyne, Smithsonian Aerospace Museum, "Preservation of American Aerospace Heritage: A Status on the National Aerospace Museum."
1985 James B. Irwin, NASA Astronaut (retired), "In Search of Noah's Ark."

1986 Roy Garstang, University of Colorado, “Halley’s Comet.”
1987 Kathryn Sullivan, NASA Astronaut, “Pioneering the Space Frontier.”
1988 William E. Kelley and Dan Koblosh, Northrop Aircraft Division, “The Second Best Job in the World, the Filming of Top Gun.”
1989 Brig. Gen. Robert Stewart, U.S. Army Strategic Defense Command, “Exploration in Space: A Soldier-Astronaut’s Perspective.”
1990 Robert Truax, Truax Engineering, “The Good Old Days of Rocketry.”
1991 Rear Admiral Thomas Betterton, Space and Naval Warfare Systems Command, “Space Technology: Respond to the Future Maritime Environment.”
1992 Jerry Waldvogel, Clemson University, “On Getting There from Here: A Survey of Animal Orientation and Homing.”
1993 Nicholas Johnson, Kaman Sciences, “The Soviet Manned Lunar Program.”
1994 Steve Saunders, JPL, “Venus: Land of Wind and Fire.”
1995 Jeffrey Hoffman, NASA Astronaut, “How We Fixed the Hubble Space Telescope.”
1996 William J. O’Neil, Galileo Project Manager, JPL, “PROJECT GALILEO: JUPITER AT LAST! Amazing Journey—Triumphant Arrival.”
1997 Robert Legato, Digital Domain, “Animation of Apollo 13.”
1998 Jeffrey Harris, Space Imaging, “Information: The Defining Element for Superpowers-Companies & Governments.”
1999 Robert Mitchell, Jet Propulsion Laboratories, “Mission to Saturn.”
2000 Dr. Richard Zurek, JPL, “Exploring the Climate of Mars: Mars Polar Lander in the Land of the Midnight Sun.”
2001 Dr. Donald C. Fraser, Photonics Center, Boston University, “The Future of Light.”
2002 Bradford W. Parkinson, Stanford University, “GPS: National Dependence and the Robustness Imperative.”
2003 Bill Gregory, Honeywell Corporation, “Mission STS-67, Guidance and Control from an Astronaut’s Point of View.”
2004 Richard Battin, MIT, “Some Funny Things Happened on the Way to the Moon.”
2005 Dr. Matt Golombeck, Senior Scientist, MER Program, JPL, “Mars Science Results from the MER Rovers.”
2006 Mary E. Kicza, Deputy Assistant Administrator for Satellite and Information Services, NASA, “NOAA: Observing the Earth from Top to Bottom.”
2007 Patrick Moore, Consulting Senior Life Scientist, SAIC and the Navy Marine Mammal Program, “Echolocating Dolphins in the U.S. Navy Marine Mammal Program.”
2008 Dr. Ed Hoffman, Director, NASA Academy of Program and Project Leadership, “The Next 50 Years at NASA – Achieving Excellence.”
2009 William Pomerantz, Senior Director for Space, The X Prize Foundation, “The Lunar X Prize.”
2010 Berrien Moore, Executive Director, Climate Central, “Climate Change and Earth.”
2011 Joe Tanner, Former Astronaut; Senior Instructor, University of Colorado, “Building Large Objects in Space.”
2012 Greg Chamitoff, Ph.D., NASA Astronaut, “Completing Construction of the International Space Station — The Last Mission of Space Shuttle Endeavour.”
2013 Thomas J. “Dr. Colorado” Noel, Ph.D., Professor of History and Director of Public History, Preservation & Colorado Studies at University of Colorado Denver, “Welcome to the Highest State: A Quick History of Colorado.”

For 2014 a change was made to replace the banquet dinner with a less formal social networking event where conference attendees would have a designated time and venue to encourage building relations. The keynote speaker event of the evening was retained and provided stimulating discussion and entertainment in 2014. Subsequent years retained the networking event but eliminated the speaker in favor of more time to interact with other conference attendees.

2014 Neil Dennehy, Goddard Space Flight Center and Stephen “Phil” Airey, European Space Agency, “Issues Concerning the GN&C Community.”

In addition to providing for an annual exchange of the most recent advances in research and technology of astronautical guidance and control, for the first fourteen years the Conference featured a full-day tutorial in a specific area of current interest and value to the guidance and control experts attending. The tutor was an academic or researcher of special prominence in the field. These lecturers and their topics were:

Tutorials

1978 Professor Dan DeBra, Stanford University, "Navigation"
1979 Professor William L. Brogan, University of Nebraska, "Kalman Filters Demystified"
1980 Professor J. David Powell, Stanford University, "Digital Control"
1981 Professor Richard H. Battin, Massachusetts Institute of Technology, "Astrodynamics: A New Look at Old Problems"
1982 Professor Robert E. Skelton, Purdue University, "Interactions of Dynamics and Control"
1983 Professor Arthur E. Bryson, Stanford University, "Attitude Stability and Control of Spacecraft"
1984 Dr. William B. Gevarter, NASA Ames, "Artificial Intelligence and Intelligent Robots"
1985 Dr. Nathaniel B. Nichols, The Aerospace Corporation, "Classical Control Theory"
1986 Dr. W. G. Stephenson, Science Applications International Corporation, "Optics in Control Systems"
1987 Professor Dan DeBra, Stanford University, "Guidance and Control: Evolution of Spacecraft Hardware"
1988 Professor Arthur E. Bryson, Stanford University, "Software Application Tools for Modern Controller Development and Analysis"
1989 Professor John L. Junkins, Texas A&M University, "Practical Applications of Modern State Space Analysis in Spacecraft Dynamics, Estimation and Control"
1990 Professor Laurence Young, Massachusetts Institute of Technology, Aerospace Human Factors"
1991 The Low-Earth Orbit Space Environment
Professor G. W. Rosborough, University of Colorado, "Gravity Models"
Professor Ray G. Roble, University of Colorado, "Atmospheric Drag"
Professor Robert D. Culp, University of Colorado, "Orbital Debris"
Dr. James C. Ritter, Naval Research Laboratory, "Radiation"
Dr. Gary Heckman, NOAA, "Magnetics"
Dr. William H. Kinard, NASA Langley, "Atomic Oxygen."

After 1991 there were no more tutorials, but special sessions or featured invited lectures served as focal points for the Conferences. In 1992 the theme was "Mission to Planet Earth" with presentations on all the large Earth Observer programs. In 1993 the feature was "Applications of Modern Control: Hubble Space Telescope Performance Enhancement Study" organized by Angie Bukley of NASA Marshall. In 1994 Jason Speyer of UCLA discussed "Approximate Optimal Guidance for Aerospace Systems." In 1995 a special session on "International Space Programs" featured programs from Canada, Japan, Europe, and South America. In 1996, and again in 1997, one of the most popular features was Professor Juris Vagners, of the University of Washington with "A Control Systems Engineer Examines the Biomechanics of Snow Skiing." In 2005, Angie Bukley chaired a tutorial session "University Work on Precision Pointing and Geolocation." In 2006, a special day for U.S. citizens only was inserted at the beginning of the Conference to allow for topics that were limited due to ITAR constraints. In 2007, two special invited sessions were held: "Lunar Ambitions—The Next Generation" and "Project Orion—The Crew Exploration Vehicle." In 2008, a special panel addressed "G&C Challenges in the Next 50 Years." The 2009 Conference featured a special session on "Constellation Guidance, Navigation, and Control." In 2013, the nail-biting but successful landing of Curiosity on Mars inspired a special session on "Entry, Descent and Landing Flight Dynamics." In 2015 and 2017 the Orion capsule development resulted in special sessions on the GN&C aspects of capsule design. In 2017 the extensive list of technology demonstration missions performed in Europe inspired a session on “European Technology Demonstrations.”

From the beginning the Conference has provided extensive support for students interested in aerospace guidance and control. The Section, using proceeds from this Conference, annually gives $2,000 in the form of scholarships at the University of Colorado, one to the top Aerospace Engineering Sciences senior, and one to an outstanding Electrical and Computer Engineering senior, who has an interest in aerospace guidance and control. The Section has assured the continuation of these scholarships in perpetuity through an $85,000 endowment. The Section supports other space education through grants to K-12 classes throughout the Section at a rate of over $10,000 per year. All this is made possible by this Conference.

The student scholarship winners attend the Conference as guests of the American Astronautical Society, and are recognized at the banquet where they are presented with scholarship plaques. These scholarship winners have gone on to significant success in the industry.

Scholarship Winners

	Aerospace Engineering Sciences	Electrical and Computer Engineering
1981	Jim Chapel	
1982	Eric Seale	
1983	Doug Stoner,	John Mallon
1984	Mike Baldwin,	Paul Dassow
1985	Bruce Haines,	Steve Piche
1986	Beth Swickard,	Mike Clark
1987	Tony Cetuk,	Fred Ziel
1988	Mike Mundt,	Brian Olson
1989	Keith Wilkins,	Jon Lutz
1990	Robert Taylor,	Greg Reinacker
1991	Jeff Goss,	Mark Ortega
1992	Mike Goodner,	Dan Smathers
1993	Mark Baski,	George Letey
1994	Chris Jensen,	Curt Musfeldt
1995	Mike Jones,	Curt Musfeldt
1996	Karrin Borchard,	Kirk Hermann
1997	Tim Rood,	Ui Han
1998	Erica Lieb,	Kris Reed
1999	Trent Yang,	Adam Greengard
2000	Josh Wells,	Catherine Allen
2001	Justin Mages,	Ryan Avery
2002	Tara Klima,	Kiran Murthy
2003	Stephen Russell,	Andrew White
2004	Trannon Mosher,	Negar Ehsan
2005	Matt Edwards,	Henry Romero
2006	Arseny Dolgove,	Henry Romero
2007	Kirk Nichols,	Chris Aiken
2008	Nicholas Hoffmann,	Gregory Stahl
2009	Filip Maksimovic,	Justin Clark
2010	John Jakes,	Filip Maksimovic
2011	Weceslao Shaw-Cortez Jr.,	Andrew Tomas
2012	Jacob Hynes,	Nicholas Mati
2013	Kirstyn Johnson,	Caitlyn Cooke
2014	David Thomas,	John Kablubowski
2015	Esteban Rodriguez,	Ryan Montoya
2016	Ryan Montoya	Esteben Rodriguez

2017	Alec Weiss	Matthew Hurst
2018	Marika Schubert	Ryan Aronson

In 2013, in an effort to increase student involvement, a special *Student Paper Session* was added to the program. This session embraces the wealth of research and innovative projects related to spacecraft GN&C being accomplished in the university setting. Papers in this session require a student as the primary author and presenter, and address hardware and software research as well as component, system, or simulation advances. Papers are adjudicated based on level of innovation, applicability and fieldability to near-term systems, clarity of written and verbal delivery, number of completed years of schooling and adherence to delivery schedule.

Student Paper Winners

2013 1st Place: Nicholas Truesdale, Kevin Dinkel, Jedediah Diller, Zachary Dischnew, "Daystar: Modeling and Testing a Daytime Star Tracker for High Altitude Balloon Observatories"

2nd Place: Christopher M. Pong, Kuo-Chia Liu, David W. Miller, "Angular Rate Estimation from Geomagnetic Field Measurements and Observability Singularity Avoidance during Detumbling and Sun Acquisition"

3rd Place: Gregory Eslinger, "Electromagnetic Formation Flight Control Using Dynamic Programming"

2014 1st Place: Dylan Conway, Brent Macomber, Kurt A. Cavalieri, John L. Junkins, "Vision-Based Relative Navigation Filter for Asteroid Rendezvous"

2nd Place: Robyn M. Woollands, John L. Junkins, "A New Solution for the General Lambert Problem"

3rd Place: Alex Perez, "Closed-Loop GN&C Linear Covariance Analysis for Mission Safety"

2015 1st Place: Andrew Liounis, Alexander Entrekin, Josh Gerhard, John Christian, "Performance Assessment of Horizon-Based Optical Navigation Techniques"

2nd Place: J. Micah Fry, "Aerodynamic Passive Attitude Control: A New Approach to Attitude Propagation and a Nano-satellite Application"

3rd Place: Siamak Hesar, Jeffrey S. Parker, Jay McMahon, George H. Born, "Small Body Gravity Field Estimation Using Liaison Supplemented Optical Navigation"

2016 1st Place: Brian C. Fields, Shawn M. Kocis, Kerri L. Williams, and Mark Karpenko, "Hardware-in-the-Loop Simulator for Rapid Prototyping of CMG-Based Attitude Control Systems."

2nd Place: Ann Dietrich and Jay W. McMahon, "Error Sensitivities for Flash LIDAR Based Relative Navigation around Small Bodies"

3rd Place: Kevin D. Anderson, Darryll J. Pines, and Suneel I. Sheikh, "Investigation of Combining X-ray Pulsar Phase Tracking Estimates to Form a 3D Trajectory"

2017 1st Place: Simon Shuster, Andrew J. Sinclair, and T. Alan Lovell, "Uncertainty Analysis for Initial Relative Orbit Determination Using Time Difference of Arrival Measurements"

2nd Place: Himangshu Kalita, Ravi Teja Nallapu, Andrew Warren, and Jekan Thangavelautham, "Guidance, Navigation and Control of Multirobot Systems in Cooperative Cliff Climbing"

3rd Place: Max Rogovin and Brian Kester, "Two-Axis Stability of a High-Altitude Balloon Payload"

2018 1st Place: F. Franquiz, B. Udrea, M. Balas, "Optimal Rate Observability Trajectory Planning For Proximity Operations Using Angles-Only Navigation"

2nd Place: B. Bercovici, J. McMahon, "Autonomous Shape Determination Using Flash-Lidar Observations and Bezier Patches"

3rd Place: D. Jennings, J. Davis, P. Galchenko, H. Pernicka, "Validation of a GNC Algorithm Using a Stereoscopic Imaging Sensor to Conduct Close Proximity Operations"

In 2015 the AAS Rocky Mountain Section partnered with the University of Colorado and hosted the inaugural STEM SCAPE conference on Saturday, which provided an introduction for the students to working in a STEM field and motivated them to pursue professional careers in aerospace engineering. This highly successful session brought in high school students, college students and included a design project, panel discussions, an opportunity to meet industry representatives, practice interviews for the college students and a keynote speech. This event was continued in 2016, building on the prior year and again reaching over 100 high school and college students.

The Rocky Mountain Section of the American Astronautical Society established the Rocky Mountain Guidance and Control Committee, chaired *ex-officio* by the next Conference Chair, to prepare and run the annual Conference. The Conference, now named the AAS Guidance, Navigation and Control Conference, and sponsored by the national AAS, annually attracts about 200 of the nation's top specialists in space guidance, navigation and control.

	Conference Chair	**Attendance**
1978	Robert L. Gates	83
1979	Robert D. Culp	109
1980	Louis L. Morine	130
1981	Carl Henrikson	150
1982	W. Edwin Dorroh, Jr.	180
1983	Zubin Emsley	192
1984	Parker S. Stafford	203
1985	Charles A. Cullian	200
1986	John C. Durrett	186
1987	Terry Kelly	201
1988	Paul Shattuck	244
1989	Robert A. Lewis	201
1990	Arlo Gravseth	254
1991	James McQuerry	256
1992	Dick Zietz	258
1993	George Bickley	220
1994	Ron Rausch	182
1995	Jim Medbery	169
1996	Marv Odefey	186
1997	Stuart Wiens	192
1998	David Igli	189
1999	Doug Wiemer	188
2000	Eileen Dukes	199
2001	Charlie Schira	189
2002	Steve Jolly	151
2003	Ian Gravseth	178
2004	Jim Chapel	137
2005	Bill Frazier	140
2006	Steve Jolly	182
2007	Heidi Hallowell	206
2008	Michael Drews	189
2009	Ed Friedman	160
2010	Shawn McQuerry	189
2011	Kyle Miller	161
2012	Michael Osborne	139
2013	Lisa Hardaway	181
2014	Alexader May	180
2015	Ian Granvseth	195
2016	David Chart	216
2017	Reuben Rohrschneider	201
2018	Cheryl Walker	236

The AAS Guidance, Navigation and Control Technical Committee, with its national representation, provides oversight to the local conference committee. W. Edwin Dorroh, Jr., was the first chairman of the AAS Guidance and Control Committee; from 1985 through 1995 Bud Gates chaired the committee; from 1995 through 2000, James McQuerry chaired the committee. From 2000 through 2007, Larry Germann chaired this committee, and James McQuerry has chaired the committee since. The committee meets every year at the Conference, and also sometimes at the summer Guidance and Control Meeting, or at the fall AAS Annual Meeting.

The AAS Guidance, Navigation and Control Conference, hosted by the Rocky Mountain Section in Colorado, continues as the premier conference of its type. As a National Conference sponsored by the AAS, it promises to be the preferred idea exchange for guidance, navigation and control experts for years to come.

On behalf of the Conference Committee and the Section,

Cheryl A. H. Walker, Ph.D.
Lockheed Martin
Denver, Colorado

PREFACE

This year marked the 41st anniversary of the AAS Rocky Mountain Section's Guidance, Navigation and Control Conference. It was held in Breckenridge, Colorado at the Beaver Run Resort from February 1 – 7, 2018. The planning committee and the national chairs did an outstanding job in creating a highly-technical conference experience, and I extend many thanks to all those involved.

The conference began this year on Thursday morning with the classified sessions that extended into Friday morning and were hosted at The Aerospace Facility in Colorado Springs, Colordo. This offered a unique opportunity to share and network at a level usually unavailable to many in our GN&C community. The two sessions were titled *Classified Sessions on Advances in G&C and Recent Experiences***.**

The traditional five day conference format officially began on Saturday morning with an impressive *Student Innovations in GN&C* session featuring a student competition with scholarship prizes. Following the student paper session, the conference hosted the 3rd annual STEM-SCAPE event, which introduced over 80 area high school students and 20 University of Colorado students to careers in an aerospace engineering field. To cap off the day, the *Technical Exhibits* session was held Saturday afternoon. Nearly twenty companies and organizations participated with many hardware demonstrations as well as excellent technical interchanges between conferees, vendors, and family.

We were fortunate to have NASA Astronaut, Richard Hieb give an exciting presentation to the children visiting with us at the conference. We also had a daily *Poster Session* where posters were on display so attendees could speak one-on-one with the authors during breakfast, break periods and a special Sunday poster focus time.

Other sessions during the conference examined the current state-of-the-art and other focus areas of interest to the GN&C community. The *Advanced Propulsion* and *Small Satellite GN&C* sessions were presented on Sunday morning. The *Entry Descent & Landing GN&C* and *GN&C Challenges of Asteroid Deflection* sessions took place on Sunday afternoon. Between the sessions, Hanspeter Schaub from the University of Colorado presented a tutorial entitled *Beyond the Textbook: Hands-on Demonstration of Using the Basilisk Astrodynamics Framework*.

Monday morning two concurrent sessions, *Advances in GN&C Algorithms* and *GN&C Advances to Enable New Frontiers in Crewed Spaceflight* were held. During the mid-day, the Rafael Lugo from AMA presented an ITAR tutorial, *Beyond the Textbook: Program to Optimize Simulated Trajectories II (POST2) Introductory Tutorial*. Monday evening featured the *Advances in GN&C Software and Advances in GN&C Hardware* parallel sessions.

Tuesday morning's parallel sessions included *Science Weather Enabled with an introduction by Mike Gazarik the Vice President of Engineering at Ball Aerospace,* and the *Pioneers of GN&C and Astrodynamics*. Tuesday included two Beyond the Textbook tutorials. Russell Carpenter from GSFC) and Chris D'Souza from NASA/JSC gave the tutorial *Beyond the Textbook: Nav Filter Best Practices*. Nahum Melamed and Damian Toohey from The Aerospace Corp gave the tutorial *Beyond the Textbook: Applying Missile Intercept GN&C Solutions to the Problem of Asteroid Deflection for Planetary Defense.* The Tuesday evening sessions were *Space Launch System (SLS) Navigation* and the ever-popular *Advances in RPOD*.

Finally, Wednesday morning featured the popular closing session *Recent Experiences*. This traditional session contained candid first-hand accounts of successes and failures for missions, which contain valuable lessons for the GN&C community.

The participation and support of our many colleagues in the industry helped make the 41th Annual Rocky Mountain AAS GN&C conference a great success. The technical committee, session chairs, and national chairs were unfailingly supportive and fully committed to the technical success of the conference. Special thanks also go to Carolyn O'Brien (Ret) and Amy Delay of Lockheed Martin, Lis Garratt of Ball Aerospace, and the staff at Beaver Run for their professionalism and attention to the operational details that made this conference happen!

Cheryl A. H. Walker Ph.D., Conference Chairperson
2018 AAS Guidance, Navigation and Control Conference

CONTENTS

Part II

STUDENT INNOVATIONS IN GUIDANCE, NAVIGATION AND CONTROL

Session 1

National Chairpersons:

David Geller, Utah State University

Lt. Col. Michael Sobers, United States Air Force Academy

Local Chairpersons:

Ian Gravseth, Ball Aerospace & Technologies Corp.

David Chart, Lockheed Martin Space Systems Company

The following paper was not available for publication:

AAS 18-013 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 18-001 to -010 and AAS 18-019 to -030

COMBINING ORBIT DETERMINATION AND LANDED TRANSPONDER SPIN-STATE SOLUTIONS VIA MULTI-ARC FILTERING

Andrew S. French[*] and Jay W. McMahon[†]

Accurate determination of an asteroid's spin-state is of vital importance to mission navigators and scientists. A body's spin-state is intrinsically tied to its gravitational field and its internal mass distribution. Precise pole estimates have been and are achieved via orbit determination with optical navigation and it has been shown that similar levels of accuracy can be achieved by filtering radiometric data from a landed transponder that is fixed to the body's surface. This paper examines both methods in detail and presents a method of combining these solutions via a multi-arc filtering technique. Multi-arc filtering is a process of combining filter solutions from independent filtering arcs to solve for common parameters. This technique is most commonly used in precise gravity field estimation in order to combine information from quiet periods and ignore segments that are poorly modeled or that are particularly noisy. In this paper independent pole estimates derived from orbit determination and landed transponder systems are combined into a single 'best' solution and individual arc parameters and residuals are updated.

[View Full Paper]

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AAS 18-012

RAPID MOTION CONTROL OF FLEXIBLE SPACE SYSTEMS

Adam L. Atwood,[*] Martin J. Griggs,[*]
Steven W. Wojdakowski[*] and Mark Karpenko[†]

Motion control of flexible systems typically involves moving things slowly in order to limit the magnitude of unwanted vibrations. While this approach can make designing control systems easier (e.g. decoupled control), it can have a negative impact on the overall performance of a space mission. In this paper, optimal control theory is applied to a flexible multi-body system as a whole in order to design a rapid motion control that exploits the nonlinearities and internal coupling of the multi-body system dynamics. To demonstrate the idea, a test bed is developed that allows flexible motion control experiments to be carried out in a laboratory environment. The current status of this testbed is described and the new optimal control concepts are applied for the rapid motion control of a two-link flexible manipulator subsystem. Experiments show that the rapid motion control reduces the terminal time of the maneuver profile and reduces both the 2% settling time and end-of-maneuver residual energy by about 50% compared to a conventional quadratic motion profile. [View Full Paper]

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AAS 18-014

OPTIMAL RANGE OBSERVABILITY TRAJECTORY PLANNING FOR PROXIMITY OPERATIONS USING ANGLES-ONLY NAVIGATION

Francisco J. Franquiz[*] and Bogdan Udrea[†]

A method for planning spacecraft trajectories with optimal range observability using angles-only navigation is presented. All feasible transitions of a chaser spacecraft between two relative trajectories with respect to a non-cooperative resident space object (RSO) are considered. The approach is more flexible, from an operations point of view, than point-to-point transfers and allows the mission planner to specify start and end conditions that result in any desired type of relative motion.

The dynamics are modeled by linearized relative equations of motion in a quasi-circular planetary orbit. A geometry-based metric is used to develop a cost function which evaluates observability along trajectories, given an arbitrary thrusting maneuver. The optimization procedure returns the exit and entry conditions, relative states, necessary for transfer between initial and target trajectories, respectively. By assuming impulsive maneuvers, the relative dynamics are parameterized in terms of linear relative-orbit-elements, thereby reducing the number of variables to a single time-dependent parameter per trajectory. The transfer between trajectories is constrained in terms of the fuel used per burn, collision avoidance with the RSO, eclipse conditions, and obstructions by neighboring celestial bodies in the sensor field of view.

Numerical simulation results are presented which give a representative example of proximity operations in geosynchronous orbit. A simple Monte Carlo validation procedure uses a continuous-discrete extended Kalman filter to produce preliminary navigation performance results. [View Full Paper]

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AAS 18-015

VALIDATION OF A GNC ALGORITHM USING A STEREOSCOPIC IMAGING SENSOR TO CONDUCT CLOSE PROXIMITY OPERATIONS

Donna Jennings,* Jill Davis,* Pavel Galchenko* and Henry Pernicka†

The set of guidance, navigation, and control algorithms for a satellite using a stereoscopic imaging sensor to conduct close proximity operations about a non-cooperative resident space object is used as a case study for a new means of verification and validation. This V&V method uses AGI's STK in conjunction with MATLAB to replicate mission-like sensor data as well as perform high-fidelity orbit propagation. The STK scenario acts as a truth model as well as a means to provide sensor data. These sensor data are corrupted with noise and bias and are then processed by the GNC algorithms to determine a commanded control. The commanded control is then corrupted by noise and applied to the STK scenario as an impulsive maneuver. The scenario is propagated to the next time step and the process repeats. Upon completion of the simulation, the algorithms are validated by a visual inspection of the relative trajectory. To verify the algorithms both acceptance testing and requirement evaluation are used to confirm all mission objectives are achieved. [View Full Paper]

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AAS 18-016

CONSTRUCTING A 3D SCALE-SPACE FROM IMPLICIT SURFACES FOR VISION-BASED SPACECRAFT RELATIVE NAVIGATION

Andrew P. Rhodes* and John A. Christian†

The observation and description of partially observed objects is an important aspect of spacecraft relative navigation. Approaching an object reveals keypoints on the object's surface at decreasing scale, while scale-space theory diffuses surface signals at increasing scale. This paper applies a scale-space approach to identifying surface features. While scale-space is well-studied for 2D images, the corresponding procedure for 3D surfaces is immature. Construction of a 3D scale-space is accomplished by solving the diffusion equation on an implicit surface using a backward Euler scheme. This implicit surface approach reduces the effects of irregular meshed surfaces and complicated definitions of the discrete Laplace-Beltrami operator. Two methods for scale estimation are presented that are inherent to the diffusion equation and independent of the surface. A method of keypoint localization is discussed and compared to that of image feature localization. Examples demonstrate that features of various scale are distributed across the surface models of Itokawa and Mars Global Surveyor which may be used for spacecraft relative navigation. [View Full Paper]

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AUTONOMOUS SHAPE DETERMINATION USING FLASH-LIDAR OBSERVATIONS AND BEZIER PATCHES

Benjamin Bercovici[*] and Jay W. McMahon[†]

The shape of irregular small bodies like comets or asteroids has traditionally been parametrized as a collection of low-degree surface elements, such as polyhedrons or connected quadrilaterals. The reconstruction of such shapes by means of observation data is customarily carried out on the ground, due to the computer-intensive nature of the reconstruction process. This paper proposes the use of triangular Bezier patches to fit point cloud data obtained from a Flash Lidar. Flash-Lidar measurements are a highly accurate data type well suited to autonomous space vehicles, especially in the context of operations about small bodies. Shapes comprised of Bezier triangles offer a powerful alternative to polyhedral shapes due to their ability to capture curvatures, producing shapes of resolution similar to much higher-resolution polyhedrons. A shape estimate of asteroid Itokawa reconstructed by means of our Lidar/Bezier pipeline was obtained along with a quantification of the uncertainty in the reconstructed shape. This confidence measure was found to be consistent with the effective shape fitting residuals, although underfitting errors may dominate in some areas. [View Full Paper]

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AAS 18-018

OPTIMIZING SATELLITE ORBITAL GEOMETRIES FOR GEOLOCATION USING RF LOCALIZATION

David Lujan,[*] Elias Clark[†] and T. Alan Lovell[‡]

Radio frequency (RF) localization is a method that can be used to locate an uncooperative device that is actively emitting a signal. This paper focuses on the formulation and solving of optimization problems for multi-spacecraft trajectories and formations; in particular, optimization problems involving the localization of ground-based RF transmissions. A framework for sensitivity studies was created in order to determine which types of satellite geometries will be most effective at determining transmitter locations. By calculating the time difference of arrival (TDOA) between two or three receivers with known positions, the location of the transmitter can be approximated. Parametric studies of the receivers' orbital elements with various transmitter locations provided estimates and trends for optimal orbital geometries. Additionally, a particle swarm optimizer (PSO) was developed and implementation verified results from the parametric studies.

[View Full Paper]

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ADVANCED PROPULSION

Session 3

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Christopher McLean, Ball Aerospace & Technologies Corp.

Nick Patzer, Laboratory for Atmospheric and Space Physics (LASP)

The following papers were not available for publication:

AAS 18-031 (Paper Withdrawn)

AAS 18-036 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 18-038 to -040

AAS 18-032

SOLAR ELECTRIC PROPULSION ARCHITECTURAL OPTIONS FOR FUTURE APPLICATIONS ON BALL CONFIGURABLE PLATFORMS

William D. Deininger,[*] Scott Mitchell,[†] Richard Dissly,[‡] Scott Enger,[§] Suzan Green,[**] Mike O'Hara,[††] JC Soto[‡‡] and Jonathan Weinberg[§§]

Ball Aerospace has studied the Solar Electric Propulsion (SEP) implementation for the past 20 years. Work has included concept development for ARM, SEP demonstration mission options, modular SEP tug definition, launch vehicle SEP-based upper stages, ESPA-class SEP-Sat configurations, micro-impulse sciencecraft precise positioning, micro-impulse formation flying and focused interplanetary spacecraft designs for high ΔV, typically outer planet and small body, science missions. Ball has looked at pulsed and continuous thrust SEP implementations, systems ranging from watts to tens of kilowatts, μN of thrust at 8,000 s specific impulse to tens of newtons of thrust at 2500 s specific impulse. There have been numerous improvements in EP and power generation technologies over the past 5 years. The realization of the MegaFlex and MegaRosa solar arrays and flight demo of MegaRosa are key on the power side. Micro-thruster development and Hall thruster system development at both high power and low power are enabling. Ball continues to examine SEP options for mission applications on Ball Configurable Platforms (BCP) in light of these new developments. Mission applications in various Earth orbits and interplanetary space are considered. This paper summarizes recent Ball SEP activities in the areas of SEP tug concepts, SEP demonstration mission, outer planet science missions and EELV Secondary Payload Adapter (ESPA)-class SEPSats. Ongoing work focuses on ESPA-class, SEPSat capabilities definition and SEP accommodation on small BCP platforms. Mission options starting in both LEO and GTO were explored with multiple thruster system types. BCP ESPA-class, SEPSats with the highest Isp system (ion) can escape from Earth's gravity, in some cases with sufficient C3 to go to Venus or Mars. [View Full Paper]

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AAS 18-033

SPACE STORABLE HYBRID ROCKET TECHNOLOGY DEVELOPMENT

Ashley C. Karp,* Barry Nakazono† and David Vaughan‡

Hybrid rocket propulsion is gaining a great deal of interest for space storable and low temperature applications. Typical hybrid propellants have been shown to survive over a wide range of temperatures, minimizing the need for thermal control. This ability to survive in low temperature environments, coupled with their high performance (comparable to liquid bipropellants) and ability to restart has made them viable candidates for a variety of missions. A technology development program at the Jet Propulsion Laboratory over the last three years has focused on increasing the Technology Readiness Level (TRL) of hybrid rockets for a potential Mars Ascent Vehicle (MAV), In Situ Resource Utilization (ISRU) and Interplanetary SmallSat applications. Results of this technology development will be presented. [View Full Paper]

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AAS 18-034

EARTH TO MARS ABORT ANALYSIS FOR HUMAN MARS MISSIONS

C. Russell Joyner II,[*] James F. Horton,[†] Timothy Kokan,[‡] Daniel J. H. Levack[§] and Frederick Widman[**]

Future human exploration missions to Mars are being studied by NASA and industry. Several approaches to the Mars mission are being examined that use various types of propulsion for the different phases of the mission. The choice and implementation of certain propulsion systems can significantly impact mission performance in terms of trip time, spacecraft mass, and especially mission abort capability. Understanding the trajectory requirements relative to the round-trip Earth to Mars mission opportunities in the 2030's and beyond is important in order to determine the impact of trajectory abort capability. Additionally, some propulsion choices for the crew vehicle can enable mission abort trajectories while others will most likely provide less flexibility and increase mission risk.

This paper focuses on recent modeling of Earth to Mars abort scenarios for human missions to determine the capability to provide fast returns to Earth. The modeling assumed that the abort would occur after the Mars crew vehicle has been injected along the path to Mars (i.e., after the Trans Mars Injection (TMI) burn). These aborts have been defined as well as the timing of fly-by aborts to quickly return crew to Earth.

These abort trajectory studies are based on missions NASA defined during the Evolvable Mars Campaign (EMC) with crew going to Mars in 2033, 2039, 2043 and 2048. Detailed trajectory analysis was performed with the NASA Copernicus program for the several crew missions that were in the EMC as well as other new missions being considered using finite-burn low thrust electric propulsion. The goal was to determine how the heliocentric trajectory elements change and the "abort trajectory" impulse requirements.

Abort scenarios that were studied included fast returns N-days after TMI as well as fly-by aborts and multiple revolution cases, using all available propellants (e.g., main propulsion system and reaction control system (RCS)) to provide the required abort velocity change. Trajectories were investigated for impulsive maneuvers and for finite burn cases and the abort timelines for each are examined and compared.

This paper and presentation will focus on the Copernicus trajectory analysis results that were performed to determine the abort trajectories that altered the primary mission to return to Earth as soon as possible. [View Full Paper]

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AAS 18-035

FUSION AND FISSION/FUSION HYBRID PROPULSION CONCEPTS FOR RAPID EXPLORATION OF THE SOLAR SYSTEM

Jason Cassibry,[*] Robert Adams,[†] Mike Lapointe,[‡]
Ross Cortez[§] and Bryan Winterling[§]

Pulsed fusion and fission/fusion hybrid propulsion systems can enable rapid interplanetary trip times (~1 year to Jupiter, ~4 years to Neptune) and precursor interstellar missions with flyby times of 50 to 200 years to the nearest stars. In advanced, pulsed systems, a single pulse contributing to propulsion consists of a micro-explosion of fusion or fission fragments which are redirected in a nozzle to produce an impulse. The frequency of these pulses scales the thrust of the system. In this paper we present some of the concepts which are being studied at collaboratively with MSFC, LANL, and other groups. This includes pulsed fission fusion (PUFF), magneto-kinetic compression of fuel fusion pellets through a convergent magnetic nozzle, plasma jet driven magneto-inertial fusion, and z-pinch of lithium deuteride wires. 3D simulations of targets which could exceed a gain of unity (more energy out than input to the system) of select cases will be presented using SPFMax, a smooth particle fluid with Maxwell equation solver. Simulations of the expansion in a nozzle will also be given. Using straight line trajectory and patched conic simulations, trip times and corresponding initial vehicle mass are presented for notional missions of interest, including flyby, rendezvous, and outer planet sample return to make comparisons with existing technologies. [View Full Paper]

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AAS 18-037

CONTINUOUS ELECTRODE INERTIAL ELECTROSTATIC CONFINEMENT FUSION

R. J. Sedwick,[*] A. M. Chap and N. M. Schilling

One of the greatest impediments to space exploration is a lack of abundant power, in particular as missions extend farther from the sun. Nuclear fusion, while not technically a renewable like solar photovoltaics, offers such a high energy density that the distinction becomes meaningless over foreseeable mission lifetimes. An ideal implementation of fusion power for space would be aneutronic, removing mass requirements for reactor shielding and eliminating material activation and damage. It would ideally also leverage direct energy conversion, eliminating the need for massive radiators required to support thermodynamic power conversion. Continuous Electrode Inertial Electrostatic Confinement Fusion is a concept currently under development that may lend itself to utilizing the proton-boron reaction with power conversion provided by a standing wave direct energy conversion concept. This paper presents an overview of the technology and provides a high-level, top-down system design for a 1 MW reactor. [View Full Paper]

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SMALL SATELLITE GUIDANCE, NAVIGATION AND CONTROL

Session 4

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Local Chairpersons:

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Jeffrey Parker, Advanced Space

The following paper was not available for publication:

AAS 18-046 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 18-049 to -050

AAS 18-041

GNC IMPLEMENTATIONS FOR SMALL INTERPLANETARY AND LUNAR SPACECRAFT

Matthew Baumgart, Michael Ferenc, Daniel Hegel,
Bryan Rogler and Devon Sanders*

As the capabilities of small spacecraft continue to expand, deep space missions have become an attractive application for these platforms. Examples of upcoming flight programs include the 6U MarCO cubesats headed for Mars, and the wide variety of lunar and deep-space missions slated for flight on the upcoming EM-1 launch. This paper explores a series of GNC developments implemented on the Blue Canyon Technologies (BCT) XACT attitude control system and XB-1 spacecraft bus to address the challenges of these missions. Thruster operations for momentum control and orbit adjustment, Delta-V operations, deep space trajectory maintenance, and autonomy are emphasized.

[View Full Paper]

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MOBILITY AND SCIENCE OPERATIONS ON AN ASTEROID USING A HOPPING SMALL SPACECRAFT ON STILTS

Himangshu Kalita,[*] Stephen Schwartz,[†]
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There are thousands of asteroids in near-Earth space and millions in the Main Belt. They are diverse in physical properties and composition and are time capsules of the early solar system. This makes them strategic locations for planetary science, resource mining, planetary defense/security and as interplanetary depots and communication relays. Landing on a small asteroid and manipulating its surface materials remains a major unsolved challenge fraught with high risk. The asteroid surface may contain everything from hard boulders to soft regolith loosely held by cohesion and very low-gravity. Upcoming missions Hayabusa II and OSIRIS-REx will perform touch and go operations to mitigate the risks of 'landing' on an asteroid. This limits the contact time and requires fuel expenditure for hovering. An important unknown is the problem of getting stuck or making a hard impact with the surface. The Spacecraft Penetrator for Increasing Knowledge of NEOs (SPIKE) mission concept will utilize a small-satellite bus that is propelled using a xenon-fueled ion engine and will contain an extendable, low-mass, high-strength boom with a tip containing force-moment sensors. SPIKE will enable contact with the asteroid surface, where it will perform detailed regolith analysis and seismology as well as penetrometry, while keeping the main spacecraft bus at a safe distance. Using one or more long stilts frees the spacecraft from having to hover above the asteroid and thus substantially reduces or eliminates fuel use when doing science operations. This enables much longer missions that include a series of hops to multiple locations on the small-body surface. We consider a one-legged system, modelled as an inverted pendulum, where the balanced weight is only 10-100 mN. The objective is to balance the spacecraft upon the boom-tip touching the surface. Furthermore, the spacecraft will disengage with the asteroid and hop to another location. The reaction times in the milligravity environment of a km-sized asteroid are much less stringent than the inverted pendulum task on Earth. However, there remain uncertainties with the asteroid surface material, hardness and overall risk posture on the mission. Using this proposed design, we present a preliminary landing system and analyze the implications of GNC on science operations. The proposed spacecraft design and controls approach is a major departure from conventional spacecraft with amphibious capabilities of a lander and flyby vehicle packaged in one.

[View Full Paper]

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AAS 18-043

DYNAMIC PROGRAMMING BASED ATTITUDE TRAJECTORIES FOR UNDERACTUATED CONTROL SYSTEMS

Vedant* and Alexander Ghosh†

A purely magnetic Attitude Control System (ACS), utilizing only magnetorquers, on a satellite in low Earth orbit is an underactuated system. The control torque is limited to an S1 sphere, such that the S1 sphere is always perpendicular to the local magnetic field. Since the local magnetic field is a relatively well-known function of the orbital position, attitude and time, the directions of the under actuation can be estimated beforehand. This study demonstrates ways to generate attitude trajectories while minimizing the control effort, assuming the final desired point is within the reachable set of the system dynamics and the time horizon. Such trajectories are generated by discretizing the state space and obtaining the optimal paths between any two reachable states, and then solving the Bellman equation, composing a set of optimal paths to obtain the final trajectory. The optimal paths between the discretized points can be determined beforehand, thereby only requiring the Bellman equation to be solved, consequently providing speed benefits over traditional methods. The proposed dynamic programming based solutions are presented for attitude trajectories for the upcoming CubeSat missions flying on the University of Illinois' IlliniSat-2 CubeSat bus, which uses a purely magnetic attitude determination and control system. [View Full Paper]

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AAS 18-044

SENSOR FUSION FOR ATTITUDE DETERMINATION

Vedant,[*] Yukti Kathuria[†] and Alexander Ghosh[‡]

The University of Illinois-developed IlliniSat-2 CubeSat bus has multiple redundant attitude determination sensors. To improve the overall system reliability, a sensor fusion algorithm has been developed. This study demonstrates a real-time sensor fusion algorithm that collects the data from each type of sensor and serves as a preprocessing of the sensor data, passing the best estimate of the sensor data to the determination algorithm. The algorithm is also capable of identifying failed sensors and preventing them from adversely affecting attitude determination. The study concludes with HIL tests of the sensor fusion algorithm using CubeSim, an attitude determination and control simulator, demonstrating the fusion of IMU and magnetometer sensors. [View Full Paper]

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AAS 18-045

ADVANCED GNC TECHNIQUES FOR AUTONOMOUS RENDEZVOUS PROXIMITY OPERATIONS AND DOCKING OF SMALL SATELLITES

Christopher W. T. Roscoe,[*] Jason J. Westphal,[*] Jason R. Crane[*] and Islam I. Hussein[*]

The spacecraft Rendezvous, Proximity Operations and Docking (RPOD) mission has been actively studied going back to and before the days of the NASA's Gemini program. The proliferation of small satellites with ever greater sensor and computational capability has opened the possibility of robustly performing these operations with small satellites and without the need for human-in-the-loop control methodologies. The CubeSat Proximity Operations Demonstration (CPOD) mission will demonstrate rendezvous, proximity operations, and docking with a pair of 3U CubeSats using miniaturized components and sensors. The goal of this mission is to develop small spacecraft technologies with game-changing potential and validate these technologies via spaceflight. This paper will present an overview of the RPO GNC subsystem, which employs a semi-autonomous approach to performing RPOD operations where human controllers are in the loop only for key phase transitions. Also presented is an advanced hybrid control algorithm for performing RPOD operations fully autonomously, along with high-fidelity simulation results.

[View Full Paper]

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AAS 18-047

VERIFICATION OF ATTITUDE DETERMINATION AND CONTROL CAPABILITIES FOR CUBESAT-CLASS SPACECRAFT

Matt Sorgenfrei,* Jordan Liss† and Dayne Kemp‡

An important element of verification and validation of attitude determination and control technologies is developing a trustworthy external reference. One approach to generating an external reference recently undertaken at NASA Ames Research Center is the use of the open source AprilTag software package. This software, using inputs from a commercial-off-the-shelf high-definition web camera, can track the motion of visual targets mounted on a test article and report back roll, pitch, yaw, and Cartesian position information in real time. This paper will describe the implementation of the AprilTag software for CubeSat-class attitude determination and control technologies, and will compare attitude data collected using AprilTag to data generated internally on a CubeSat testbed. It is shown that the external reference can track the attitude of a given testbed with an accuracy of 5 degrees or better, which is sufficient for many current and future CubeSat missions. [View Full Paper]

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AAS 18-048

GENERALIZATION OF THE EFFECTS OF ATMOSPHERIC DENSITY UNCERTAINTIES ON THE PROBABILITY OF COLLISION

Charles D. Bussy-Virat,[*] Aaron J. Ridley[†] and Joel W. Getchius[‡]

The motion of satellites below 1,000 km is greatly influenced by the density of the surrounding atmosphere through drag. Unfortunately, atmospheric density is hard to model, posing a real challenge in the realm of collision avoidance where trajectories of spacecraft need to be predicted particularly accurately. Current efforts attempt to consider the effects of density uncertainties in the collision risk assessment. This study seeks to generalize these effects by quantifying the uncertainty in the probability of collision for different encounter geometries and ballistic coefficients. [View Full Paper]

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ENTRY DESCENT AND LANDING GUIDANCE, NAVIGATION AND CONTROL

Session 5

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Michael Osborne, Lockheed Martin Space Systems Company

The following paper was not available for publication:

AAS 18-055 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 18-056 to -060

AAS 18-051

COBALT: TERRESTRIAL FLIGHT TEST OF LANDING NAVIGATION USING LANDER VISION SYSTEM WITH NAVIGATION DOPPLER LIDAR*

Steven M. Collins,† Carl R. Seubert,‡ Ara Kourchians,§ Carlos Y. Villalpando and John M. Carson III††**

COBALT (CoOperative Blending of Autonomous Landing Technologies) is a NASA technology development and test program to advance precision landing capabilities for future soft landers. The COBALT payload demonstrated terrain relative navigation utilizing the Lander Vision System and Navigation Doppler Lidar sensors on the Masten Space Systems Xodiac rocket. In spring 2017, the program culminated in two open-loop free flights to 500 m altitude with downrange diverts of 300 m. The COBALT system performed well, navigating within meters of the Xodiac vehicle's GPS-based solution. This paper outlines details of the navigation filter and its performance during the test campaign. [View Full Paper]

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‡ COBALT Flight Test Lead, ⊗
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AAS 18-052

AEROCAPTURE SYSTEM OPTIONS FOR DELIVERY OF SMALL SATELLITES TO MARS

G. Falcone,[*] J. W. Williams[†] and Z. R. Putnam[‡]

Small satellites may provide a low-cost platform for targeted science investigations in the Mars system. With current technology, small satellites require ride shares with larger orbiters to capture into orbit, limiting the range of orbits available to small satellite mission designers. Successful development of a small satellite aerocapture capability would allow small satellite mission designers to choose the orbit most appropriate for a science investigation while enabling small satellite ride shares on any mission to Mars. A generic small satellite aerocapture system is assessed for use at Mars across a range of small satellite payloads, approach trajectories, and destinations in the Mars system. The aerocapture system uses drag modulation for trajectory control to ensure successful orbit insertion. Analyses include assessment of the sensitivity of the entry corridor size to the ballistic-coefficient ratio, the effectiveness of real-time aerocapture guidance and control algorithms, aerocapture system-level impacts of different target orbits, and development of requirements and recommendations for the development of a small satellite aerocapture system. Results indicate that a discrete drag-modulation aerocapture system may provide an orbit-insertion capability for small satellites with modest propulsion requirements.

[View Full Paper]

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AAS 18-053

ENTRY, DESCENT, AND LANDING PERFORMANCE FOR A MID-LIFT-TO-DRAG RATIO VEHICLE AT MARS

Breanna J. Johnson,* Ellen M. Braden,* Ronald R. Sostaric,*
Christopher J. Cerimele† and Ping Lu‡

In an effort to mature the design of the Mid-Lift-to-Drag ratio Rigid Vehicle (MRV) candidate of the NASA Evolvable Mars Campaign (EMC) architecture study, end-to-end six-degree-of-freedom (6DoF) simulations are needed to ensure a successful entry, descent, and landing (EDL) design. The EMC study is assessing different vehicle and mission architectures to determine which candidate would be best to deliver a 20 metric ton payload to the surface of Mars. Due to the large mass payload and the relatively low atmospheric density of Mars, all candidates of the EMC study propose to use Supersonic Retro-Propulsion (SRP) throughout the descent and landing phase, as opposed to parachutes, in order to decelerate to a subsonic touchdown. This paper presents a 6DoF entry-to-landing performance and controllability study with sensitivities to dispersions, particularly in the powered descent and landing phases. [View Full Paper]

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AAS 18-054

FUEL-OPTIMAL AND APOLLO POWERED DESCENT GUIDANCE COMPARED FOR HIGH-MASS MARS MISSION

Ping Lu*

A human Mars mission will necessitate a significantly higher landing mass and landing precision than in any robotic missions ever attempted so far. The need for all-propulsive descent and landing for such a high-mass entry, descent, and landing (EDL) mission further increases the propellant mass fraction. The propellant usage required by the powered descent guidance algorithm can have a huge implication on the mission. In this work we set out to gain an understanding of how the propellant performance compares between an advanced fuel-optimal powered descent guidance algorithm and the venerable Apollo powered descent guidance in a high-mass Mars EDL mission. It is revealed that the powered descent initiation (PDI) condition for, and the time-to-go used in, the Apollo guidance affect greatly the propellant usage, under otherwise the same condition. Yet there has been thus far a lack of systematic and effective approaches to *autonomously* determine favorable PDI condition and time-to-go for ensured landing and good propellant performance of the Apollo guidance. In this paper a method is developed that makes use of a capability of a most recent fuel-optimal powered descent guidance algorithm to determine online a best PDI condition and the corresponding time-to-go for the Apollo guidance, based on the actual flight condition. It is shown that with this adaptive PDI logic the Apollo powered descent guidance can achieve a propellant performance that is very close to the optimal propellant consumption for a high-mass Mars EDL mission, while maintaining high landing precision. [View Full Paper]

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GUIDANCE, NAVIGATION AND CONTROL CHALLENGES OF ASTEROID DEFLECTION

Session 6

National Chairperson:

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Local Chairpersons:

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Charlie Schira, PlanetiQ

The following paper numbers were not assigned:

AAS 18-066 to -070

AAS 18-061

DYNAMICS AND CONTROL OF A TETHERED ENHANCED GRAVITY TRACTOR PERFORMING ASTEROID DEFLECTION

Haijun Shen,[*] Carlos M. Roithmayr[†] and Yingyong Li[‡]

The dynamics and control of an Enhanced Gravity Tractor (EGT) augmented with a tether for deflecting an asteroid are studied. A conventional EGT consists of collected asteroidal mass collocated with the spacecraft. Because of the presence of a tether, the collected mass is placed where the EGT would have been without a tether, and the spacecraft is placed farther away from the asteroid. Doing so improves the fuel efficiency and safety margin of the EGT operation without significantly sacrificing the gravitational attraction between the asteroid and the EGT. The tether is modeled as a series of particles connected by spring-dashpot systems. Physical properties of the tether are selected to be similar to those of the SPECTRA-1000, Kevlar-29, and Kevlar-49 fibers. It is assumed that control is applied only to the spacecraft, and there is no active control associated with the collected mass. A Proportional-Derivative (PD) controller is employed to maintain the spacecraft and the collected mass at desired positions relative to the asteroid. Numerical simulations of tethered EGT operations at 2008 EV5, Itokawa, Apophis, and a fictitious ellipsoidal asteroid are performed. It is demonstrated that a PD controller is capable of accomplishing the control objectives. The gravity gradient and the control force keep the tether stretched throughout a normal tethered EGT operation, and the load on the tether is well within the design limit of the tether material. While including multiple particles in the tether model is essential in capturing details of tether vibration, the number of particles does not significantly affect the motions of the collected mass and the spacecraft. In addition, the distance from the asteroid mass center to the collected mass should be chosen judiciously in the case of a rotating slender asteroid; some distance ranges should be avoided as excessive lateral oscillations can be excited by resonance between the asteroid rotation and tether pendular motion. [View Full Paper]

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AAS 18-062

OSIRIS-REX NAVIGATION PERFORMANCE DURING FIRST LEG OF OUTBOUND CRUISE

Peter G. Antreasian,* Jason M. Leonard,† Jim V. McAdams,† Michael C. Moreau,‡ Brian Page,† Daniel R. Wibben† and Kenneth E. Williams†

The NASA New Frontiers-class OSIRIS-REx mission is currently midway on its two-year interplanetary trajectory to rendezvous with the rare B-type near-earth asteroid Bennu (101955) in the fall of 2018. The spacecraft was directed during the first half of its journey to return to Earth for an Earth Gravity Assist (EGA) on September 22, 2017. This paper will summarize the performance of the spacecraft navigation over the first year of operations, which is exceeding expectations from prelaunch analysis. The navigation performance has benefitted from excellent performance of the main engine, trajectory correction maneuvers and attitude control system maneuvers, the well-balanced momentum desaturation maneuvers, and the quantity and quality of Deep Space Network 2-way X-band Doppler, range and delta-Differential One-way Range (ΔDOR) measurements. The combination of the ΔDOR with the traditional radio-metric data has allowed the navigation team to finely characterize the small forces influencing the spacecraft motion such as the outgassing, solar pressure and the force due to spacecraft thermal re-radiation. These forces need to be determined to a high level of accuracy to meet position requirements during proximity operations in the vicinity of Bennu. Comparisons of the current ΔV cost, maneuver magnitudes, expected orbit determination accuracies to the pre-launch analysis are presented. [View Full Paper]

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SMALL-BODY MANEUVERING AUTONOMOUS REAL-TIME NAVIGATION (SMART NAV): GUIDING A SPACECRAFT TO DIDYMOS FOR NASA'S DOUBLE ASTEROID REDIRECTION TEST (DART)

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The NASA Double Asteroid Redirection Test (DART) will be the first space experiment to demonstrate asteroid impact hazard mitigation using a spacecraft as a kinetic impactor to deflect an asteroid. The DART impactor spacecraft will hit the 170 meter diameter secondary of the Didymos binary system (Didymos B). The primary goal of DART is to measure and characterize the resulting deflection of Didymos B by the kinetic impact. One challenge is accurately guiding the spacecraft to the center-of-figure of Didymos B. DART's optical payload will be unable to differentiate the two bodies and resolve Didymos B until a few hours prior to impact. Due to communications delay (70 second round trip light-time), it will be necessary to autonomously perform the asteroid targeting, navigation, and guidance functions onboard. The small-body maneuvering autonomous real-time navigation (SMART Nav) algorithm is being developed to guide DART to the center of Didymos B. This paper describes the design approach, the effectiveness of the algorithm, and the analysis derived from simulation that includes detailed DART spacecraft and optical payload models. [View Full Paper]

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AAS 18-064

THE RVS3000 AND RVS3000-3D LIDAR SENSORS – TEST RESULTS AND DEVELOPMENT OUTLOOK

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Thanks to its robust design and accurate measurements, the Jena-Optronik RVS LIDAR sensors are the most frequently used rendezvous- and docking sensors for space applications. They are employed on several ISS re-supply missions measuring against retroreflectors located on ISS. For future applications, like on-orbit servicing, space debris removal or planetary landing, a more powerful 3D imaging LIDAR system suitable for non-cooperative targets is required. Based on previous German and European technology development activities, the RVS3000 product family has been engineered and qualified. In this paper, an overview of the RVS3000 and RVS3000-3D technology and its possible applications in LEO ISS servicing as well as potential future space robotics activities in LEO and beyond will be provided. The technical features of the RVS3000 and RVS3000-3D sensors and the differences between the two models are presented. Also, a summary will be given on first test results obtained with RVS3000 engineering model hardware prepared in the framework of activities carried out by Jena-Optronik in the frame of an ongoing DLR German Space Agency research grant. [View Full Paper]

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AAS 18-065

OSIRIS-REX GUIDANCE NAVIGATION AND CONTROL PREPARATION FOR BENNU PROXIMITY OPERATIONS*

Ryan Olds,† Thomas Schlapkohl‡ and Jason M. Leonard§

The **O**rigins **S**pectral **I**nterpretation **R**esource **I**dentification and **S**ecurity-**R**egolith **Ex**plorer (OSIRIS-REx) mission launched in September of 2016. The primary objective of the mission is to collect a sample of regolith from the asteroid Bennu. Since launch, the OSIRIS-REx spacecraft has executed many activities and calibrations designed to prepare the mission for proximity operations at Bennu starting in late 2018. Bennu is a carbonaceous near-Earth asteroid that is approximately 500 meters in diameter. It will be the smallest body orbited and presents unique challenges for operations. This unique micro-gravity environment requires very accurate knowledge of small forces effecting the spacecraft trajectory such as thruster pulses, forces due to outgassing, solar pressure and thermal radiation. For this reason, several in-flight characterization activities have been executed during the cruise phase of the mission to better understand and model small forces affecting the spacecraft. Inevitably, there will always be some threshold level of stochastic accelerations that cannot be estimated or predicted well by deterministic models. The sensitivity to stochastic accelerations is much higher for OSIRIS-REx than for other planetary missions. Because of this, the OSIRIS-REx mission has to be agile and adapt the plans for proximity operations to be robust to stochastic accelerations. In many cases, the ground system requires robust processes for updating payload targets and maneuver designs 24 hours before execution because the ability to predict the orbit with the required precision farther in advance may not be possible. This has driven the need for enhancements to the spacecraft pointing and targeting software to be more adaptable and robust to "late updates" to orbital predictions. Mission operations for OSIRIS-REx while at Bennu will be unique and this paper will further discuss activities devoted to characterizing spacecraft small forces and adaptations to ground system processes needed for flying the mission. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL ALGORITHMS

Session 7

National Chairperson:

Mark Jackson, Blue Origin

Local Chairpersons:

Scott Piggott, University of Colorado

Tomas Ryan, Ball Aerospace & Technologies Corp.

The following paper numbers were not assigned:

AAS 18-079 to -080

AAS 18-071

CLOSED-LOOP POINTING OF THE REMOTE SENSING MAST OF THE MARS 2020 ROVER

P. Brugarolas,[*] Z. Rahman, J. Casoliva, G. Griffin, A. Johnson, Y. Cheng, S. Mohan and T. Estlin

The Mars 2020 project has baselined the addition of closed-loop pointing for the rover's Remote Sensing Mast (RSM). Pointing of the inherited remote sensing mast design (from the Mars Science Laboratory MSL Mission) is limited by backlash in the azimuth and elevation actuators and thermo-mechanical errors. The new onboard pointing system compensates for backlash by including a pointing guidance algorithm and for thermo-mechanical errors by including vision-based feedback. The new closed-loop pointing system aims to point a science instrument to better than 1 mrad when closing the loop around that science instrument imager, or to better than 2 mrad when closing the loop using the engineering navigation cameras. This paper describes the new closed loop pointing system architecture and the pointing algorithms. [View Full Paper]

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AAS 18-072

COMPARING COARSE SUN SENSOR BASED SEQUENTIAL SUN HEADING FILTERS

Thibaud Teil,* Hanspeter Schaub† and Scott Piggott‡

In a sun heading determination scenario coarse sun-sensors (CSS) can be paired with rate gyros in order to estimate attitude and spacecraft rotation rate. These paired measurements allow for a fully observable state vector. However, relying solely on coarse sun-sensor measurements for sun heading and spacecraft rotation rate estimation is sometimes advantageous. Here the challenge is to find the most robust method for attitude determination without relying on rate gyros. In such a scenario, the rotation rate of the spacecraft can be estimated in order to provide state derivative control or simply for better sun heading estimation. Therefore, the state vector is traditionally the sun direction vector and its time derivative as seen by the body frame. This paper compares four different filters for gyro-less sun heading estimation. They vary in state vectors and kinematics, with the goal of controlling or removing non-observability. In order to compare the behavior of the set of sun-sensing algorithms, a modular filtering architecture is used and its utility is demonstrated. By incorporating this architecture in the Basilisk astrodynamics software package filter performances are compared through realistic scenarios. [View Full Paper]

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AAS 18-073

AN INNOVATIVE CONTROL LAW FOR MICROCARB MICROSATELLITE

Florence Genin[*] and Frederick Viaud[†]

Global warming has become a major environment concern. It is driven by greenhouse gases, such as carbon dioxide (CO2) which is the most important greenhouse gas produced by human activity. Therefore, limiting the impact of human CO2 emissions is now a crucial international challenge. In this context, France has decided to launch the mission MICROCARB, a satellite able to monitor the carbon dioxide cycle at a global scale. The project is led by CNES in collaboration with French scientific laboratories. It will improve the understanding of the exchanges between CO2 sources and sinks, their variability and sensitivity to climatic events.

In order to meet the scientific objectives of the mission, innovative pointing modes were defined and require a challenging agility. The satellite is based on the CNES microsatellite product line, called Myriade. This platform, designed in the late 1990's, has already successfully carried more than 15 satellites. Nevertheless, the generic bus needed to be upgraded to meet MICROCARB specific needs.

This paper focuses on the Attitude and Orbit Control System (AOCS) improvements and in particular on the specific control law designed to achieve the agility required by the mission. It begins with a brief presentation of the MICROCARB mission. Then it describes the satellite with a focus on the AOCS sub-system. The third part presents the innovative control of the reaction wheels, which are set up in a pyramid configuration. This method is derived from a research work conducted by CNES and Airbus Defense and Space (ADS). The last part will detail the control law designed for the mission mode which is based on the up-to-date structured H infinity synthesis method. The performances obtained with this design will be illustrated with simulations results. The paper concludes on how these AOCS improvements allow the Myriade bus to be compliant with MICROCARB mission requirements. [View Full Paper]

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AAS 18-074

COMPLETE SOLUTION TO THE LAMBERT PROBLEM WITH PERTURBATIONS AND TARGET STATE SENSITIVITY

Blair F. Thompson,* Denise Brown* and Ryan Cobb†

A complete solution to the Lambert problem is presented in algorithm form, ready for programming. The solution is based on Battin's method and includes extensions for elimination of the inherent 180 degree transfer singularity that exists in most solutions, resolution of the direction of motion ambiguity, provision for multi-revolution solutions, and incorporation of perturbations into the solution. Included is an ancillary algorithm that uses the Lambert routine in lieu of numerical integration to compute the state transition matrix (STM), which can be used for determining sensitivity of the target state with respect to initial state errors such as navigation uncertainty and thruster imperfections, or to update the pre-maneuver state covariance to the target point arrival time. Although several solutions to the Lambert problem have been developed, Battin's method is particularly appealing because it is universal and fast without being overly complex. However, it can be challenging to extract Battin's method in complete algorithmic form from his published works, especially for the non-astrodynamicist. Moreover, many other Lambert methods fail for 180 degree orbital transfers, which is often the nearly ideal angle for many transfer scenarios (e.g., Hohmann transfer). The algorithm does not require any special subroutines or software libraries beyond common mathematical functions. It is well suited for implementation in many different programming languages for spacecraft guidance navigation and control (GNC) flight software, modeling and simulation, model verification and validation, initial orbit determination (IOD), mission analysis and design, and mission operations. The modular, stand-alone nature of the algorithm makes it relatively simple to integrate with pre-existing software routines, and to validate, verify, and maintain. The algorithm has been thoroughly tested over a wide range of orbital targeting conditions, and example benchmark cases are provided to assist with implementation and validation. [View Full Paper]

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AAS 18-075

RECOVERING TIME AND STATE FOR AUTONOMOUS NAVIGATION SYSTEMS IN DEEP SPACE

Andrew Dahir,[*] Daniel Kubitschek[†] and Scott Palo[‡]

As spacecraft become more numerous, the need for autonomous navigation becomes a greater necessity for deep space travel as communication resources become limited. When spacecraft are in deep space, communication times between a satellite and the Earth can be prohibitive and ride-sharing opportunities as well as on-board faults can leave the spacecraft without time information. This approach uses optical observations of available planets and corresponding celestial satellites (for interplanetary operations) to initially recover the approximate time and state. These observations are then followed by precise, filter-based determination of time, position and velocity from the chosen optical beacons available in interplanetary spaceflight. The innovation of this approach is to use artificial satellites and celestial bodies periodicity to initially determine time. This capability is analogous to that of advanced star trackers that can initialize themselves by identifying any star field in the celestial sphere. Being able to quickly and autonomously recover time and position from an environment with no Earth contact will advance mission safety and automation from current methods which require an Earth contact. The impact of this concept crosses both human (full loss of communication scenario) and robotic (autonomous recovery from on-board fault) exploration applications, where some form of spacecraft-to-ground communication is required to establish approximates for time and position. In both cases, the current state-of-the-art navigation systems require some knowledge of time and some approximate position to initialize the estimation process before the mission objectives can be obtained. While the solution is applicable to a wide range of missions, this paper will focus on small satellites used for solar system exploration. [View Full Paper]

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AAS 18-076

PHASE-PLANE CONTROL ALGORITHM WITH ADAPTIVE MINIMUM-IMPULSE BIT INTEGRAL CONTROL

Jack Aldrich,[*] Miguel San Martin[†] and David Bayard[‡]

The JPL-heritage proportional-derivative (PD) phase-plane control algorithm is augmented with a new algorithm that incorporates integral control action for purposes of minimizing: (i) pulse counts and (ii) the time-averaged pointing error signal. Because of the deadzone present in all JPL-heritage thruster-based phase-plane control designs, the introduction of integral action into previous proportional-integral-derivative (PID) controllers has been problematic. (Of course, PID is simple to implement in the absence of a deadzone.) In this work, a stabilizer function is introduced which compares the (always stabilizing) PD control signal with the (sometimes desirable) PID control signal. In particular, when these two signals are in harmony (i.e., correlated in sign), the PID signal is utilized. On the other hand, when the PD and PID signals do not align (in sign), it can be shown that it is best to nullify the output of the controller. Simulation results are presented which demonstrate: (i) the stability of the algorithm and (ii) the minimum pulse-count and pointing error objectives. [View Full Paper]

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AAS 18-077

IN FLIGHT REDUNDANT GYRO CALIBRATION USING AN UNSCENTED KALMAN FILTER

Lydia Salazar Dahl*

Accurate rate gyros are required for spacecraft knowledge, pointing and control. Rate gyros can have error in their orientation, scale factor and bias. Therefore, a method for gyro calibration is necessary. This paper addresses the calibration of a set of four gyros, and calculates the individual errors on each gyro rather than using the standard approach of calculating the net body frame corrections. There are advantages of using a full calibration such as better fault detection and health monitoring. Historically there exist multiple methods to calibrate gyros to star tracker measurements. The main problem is generating a reference or truth body rate from star tracker measurements. Methods include back differencing star tracker attitudes and integrating full dynamics equations. Filtering method can be performed on ground processing or in flight. Batch and recursive methods can be used. An additional complication is the existence of a fourth gyro. This causes the calibration problem to be overdetermined and additional consideration must be taken to estimate the exact calibration parameters. Ball has implemented a real time on board redundant gyro calibration filter. An Unscented Kalman Filter was chosen to provide higher accuracy for this nonlinear problem. A model substitution method was used, which uses the gyro measurements in the process model, and the star tracker measurements in the measurement model. This method does not require accurate knowledge of inertias, torques, momentum or other parameters and does not require pre-smoothing of data, nor does it introduce delay in processing. The null space measurement equation is additionally used to ensure that the correct calibration parameters are estimated for the redundant gyro set. Calibration is performed on orbit while the spacecraft executes a maneuver such as a corkscrew maneuver providing observability in each gyro axis. In flight estimation of redundant gyro calibration parameters is performed using a dual head Hydra-TC Star Tracker and set of four SIRU-E gyros. The estimated calibration parameters are then used to correct gyro readings for improved attitude determination. This paper outlines the state and measurement models, the Unscented Kalman Filter formulation, observability considerations, simulation and modeling, and performance prediction. Simulation results show this straightforward method is immune to sensitivities of other methods, and provides very accurate calibration results for tight pointing requirements. [View Full Paper]

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AAS 18-078

TOWARDS REINFORCEMENT LEARNING TECHNIQUES FOR SPACECRAFT AUTONOMY

Andrew Harris* and Hanspeter Schaub†

Machine learning techniques present one class of strategies for addressing the problem of on-board spacecraft autonomy. Deep-space exploration missions, by nature, must deal with considerable uncertainty in their mission operations, especially those that deal with hard-to-model dynamics such as atmospheric density. These challenges have arisen in concert with the development of techniques for considering and acting under uncertainty in the artificial intelligence or machine learning realms. In this work, a strategy for re-formulating the on-board maneuver decision-making problem in a framework amicable to the application of probabilistic machine learning techniques is presented using aerobraking as a demonstrative problem. Advantages and caveats of the methodology are outlined, with conceptual issues for solution approaches outlined. A simplified implementation of the autonomous aerobraking problem within an autonomy framework is presented to provide a basis for future developments in the field. [View Full Paper]

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GUIDANCE, NAVIGATION AND CONTROL ADVANCES TO ENABLE NEW FRONTIERS IN CREWED SPACEFLIGHT

Session 8

National Chairpersons:

Tim Straube, NASA-JSC

Mike Hawes, Lockheed Martin Space Systems Company

Local Chairpersons:

Ellis King, The Charles Stark Draper Laboratory, Inc.

Jastesh Sud, Lockheed Martin Space Systems Company

The following paper was not available for publication:

AAS 18-085 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 18-089 to -090

AAS 18-081

RAON: REVOLUTION IN AUTONOMOUS ORBITAL NAVIGATION

Rachit Bhatia* and David K. Geller†

The future of deep space exploration depends upon technological advancement towards improving spacecraft's autonomy and versatility. This study examines the feasibility of autonomous orbit determination using accelerometer measurements. The long term objective of this research is to ascertain specific sensor requirements to meet pre-defined mission navigation error budgets. For this paper, an Extended Kalman Filter (EKF) simulation based on a simple six degree of freedom environment model is developed. While the results are low fidelity, they can be used as a guide for more detailed and complete analysis. Traditional inertial navigation (dead reckoning and external aiding) is not considered. Instead, measurements from pairs of advanced, highly sensitive accelerometers (e.g. cold atom accelerometers), on three mutually perpendicular baselines, are used to determine gravity field gradients which are then correlated to onboard gravity maps and used to determine orbital information. [View Full Paper]

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AAS 18-082

EXPLORING THE LIMITS OF HIGH ALTITUDE GPS FOR FUTURE LUNAR MISSIONS

Benjamin W. Ashman,[*] Joel J. K. Parker,[*] Frank H. Bauer[†] and Michael Esswein[‡]

An increasing number of spacecraft are relying on the Global Positioning System (GPS) for navigation at altitudes near or above the GPS constellation itself—the region known as the Space Service Volume (SSV). While the formal definition of the SSV ends at geostationary altitude, the practical limit of high-altitude space usage is not known, and recent missions have demonstrated that signal availability is sufficient for operational navigation at altitudes halfway to the moon. This paper presents simulation results based on a high-fidelity model of the GPS constellation, calibrated and validated through comparisons of simulated GPS signal availability and strength with flight data from recent high-altitude missions including the Geostationary Operational Environmental Satellite 16 (GOES-16) and the Magnetospheric Multiscale (MMS) mission. This improved model is applied to the transfer to a lunar near-rectilinear halo orbit (NRHO) of the class being considered for the international Deep Space Gateway concept. The number of GPS signals visible and their received signal strengths are presented as a function of receiver altitude in order to explore the practical upper limit of high-altitude space usage of GPS. [View Full Paper]

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DEEP SPACE AUTONOMOUS NAVIGATION OPTIONS FOR FUTURE NASA CREWED MISSIONS

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This study focuses on deep space autonomous navigation technologies, which are becoming an increasingly important capability for upcoming missions to cis-lunar space and beyond. As crewed and uncrewed missions venture further and more frequently from the Earth they will benefit from new onboard navigation technologies which have the potential to greatly increase spacecraft autonomy from Earth-based radiometric ranging sites. In this paper we leverage linear covariance analysis methods to explore potential navigation sensor architectures to augment existing (ground-based) navigation methods for the purposes of deriving sensor specification requirements for future NASA crewed missions. The key driving navigation requirements for these missions are for the final return trajectory correction maneuver and for station keeping in the near rectilinear halo orbit at the Moon. For this study the Orion EM-1 and EM-3 missions' trajectories and requirements are used as a baseline. The measurement types evaluated include long range GPS, Earth and Moon apparent direction and diameter, lunar surface feature tracking, optical satellite tracking based on Draper's Skymark concept, lunar based navigation ground sites and orbital beacons, and X-ray pulsar navigation. The feasibility of using these techniques is presented, along with the sensor sensitivity performances. [View Full Paper]

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AAS 18-084

ORION'S POWERED FLIGHT GUIDANCE BURN OPTIONS FOR NEAR TERM EXPLORATION MISSIONS

Thomas Fill,[*] John Goodman[†] and Shane Robinson[‡]

NASA's Orion exploration spacecraft will fly more demanding mission profiles than previous NASA human flight spacecraft. Missions currently under development are destined for cislunar space. The EM-1 mission will fly unmanned to a Distant Retrograde Orbit (DRO) around the Moon. EM-2 will fly astronauts on a mission to the lunar vicinity. To fly these missions, Orion requires powered flight guidance that is more sophisticated than the orbital guidance flown on Apollo and the Space Shuttle. Orion's powered flight guidance software contains five burn guidance options. These five options are integrated into an architecture based on a proven shuttle heritage design, with a simple closed-loop guidance strategy. The architecture provides modularity, simplicity, versatility, and adaptability to future, yet-to-be-defined, exploration mission profiles. This paper provides a summary of the executive guidance architecture and details the five burn options to support both the nominal and abort profiles for the EM-1 and EM-2 missions. [View Full Paper]

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AAS 18-086

IN-FLIGHT SOFTWARE RECONFIGURATION FOR ORBIT BURNS

Daniel S. Dionne[*]

Successful execution of automated orbit burns requires complex interaction between many parts of the spacecraft flight software including navigation, targeting, guidance, controls, and mission sequencing. Each piece of the flight software requires burn-related parameters that are specific to the upcoming burn in order to operate in the desired mode, execute the desired algorithm, and fire the desired engine, among other things. To achieve this, all burn-specific parameters are stored in a burn plan and a new piece of flight software, called the Burn Plan Manager (BPM), was developed for the Orion spacecraft to provide in-flight reconfiguration of targeting, guidance, control, and mission sequencing for orbit burns. This paper describes BPM and how it interacts with the other flight software components. It describes burn plan parameters, how BPM processes burn plan data, how the burn plan and BPM affect automated mission sequencing, how ground operators interact with the burn plan and BPM to perform ground burns and handle real-time mission variations, and how BPM responds to failures in other parts of the flight software to ensure downstream recipients of BPM outputs receive the most relevant data possible. [View Full Paper]

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AAS 18-087

ORION BURN AUTOMATION RESPONSE TO FAILURES

Ryan Odegard,[*] David P. Dannemiller,[†]
Charles P. Barrett[‡] and Kara Pohlkamp[§]

Orion is designed to autonomously handle failures which could result in a catastrophic hazard. Many software and hardware failures have a system level impact if they occur during on-orbit burn operations. As a result, specific automation has been included to handle failures from burn targeting through the post-burn re-configuration. This automation is applicable to all burns during the orbit phase of flight but includes configurable parameters to provide a level of opera-tor control over the automated spacecraft. One of the primary failure responses available to Orion during a burn is to switch from performing the burn with the main engine to completing the burn using the eight lower thrust auxiliary engines. This engine downmode response includes various interactions between onboard monitoring of faults in the guidance, navigation, flight controls, and propulsion systems, in concert with vehicle sequencing in order to correctly finish critical burns. This paper details the design of the automated responses to failures during burns, including the failure triggers, automated responses, and interactions across vehicle subsystems. [View Full Paper]

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AAS 18-088

A GENERIC APPROACH FOR OPTIMAL BANG-OFF-BANG SPACECRAFT MANEUVERS

Ehsan Taheri* **and John L. Junkins†**

Optimal solutions of a large class of aerospace engineering problems reveal bang-bang and bang-off-bang structures in some or all of the control inputs. These abrupt changes introduce undesired non-smoothness into the equations of motion, and their ensuing numerical propagation, which requires special treatments. In some cases, this indicates that we need to judiciously smooth these discontinuous controls; the optimal control problem being solved may be a reduced order model of a system with flexible dynamics easily disturbed by sharp control discontinuities. Also some actuators have a finite rise time not compatible with instantaneous control discontinuity. A variety of circumstances indicate a need for a judiciously smoothed compromise away from "optimal" discontinuous control inputs. In order to alleviate these induced difficulties, a generic smoothing technique is proposed that is straightforward to implement while providing additional flexibility in the rate of change of the control. The proposed technique does not affect the standard derivation of the so-called indirect methods. In many cases, modest smoothing can be introduced with full visibility of the frequently near-negligible loss of performance relative to smoothing the discontinuous controls. The utility of these ideas are illustrated via three different problems: 1) a minimum-fuel low-thrust interplanetary trajectory design problem, 2) a minimum-fuel orbit transfer from a geostationary orbit to an L1 halo orbit in the Earth-moon restricted three-body system and 3) a rest-to-rest minimum-time attitude control problem.

[View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL SOFTWARE

Session 9

National Chairperson:

Mark Jackson, Blue Origin

Local Chairpersons:

Scott Piggott, University of Colorado

Tomas Ryan, Ball Aerospace & Technologies Corp.

The following paper numbers were not assigned:

AAS 18-099 to -100

AAS 18-091

MODULAR SOFTWARE ARCHITECTURE FOR FULLY-COUPLED SPACECRAFT SIMULATIONS

Cody Allard,[*] Manuel Diaz Ramos,[*] Patrick Kenneally,[*] Hanspeter Schaub[†] and Scott Piggott[‡]

Computer simulations of spacecraft dynamics are widely used in industry and academia to predict how spacecraft will behave during proposed mission concepts. Current technology and performance requirements have placed pressure on simulations to be increasingly more representative of the environment and the physics that spacecraft will encounter. This results in increasingly complex computer simulations. Designing the software architecture in a modular way is a crucial step to allow for ease of testing, maintaining, and scaling of the software code base. However, for complex spacecraft modeling including flexible or multi-body dynamics, modularizing the software is not a trivial task because the resulting equations of motion are fully-coupled nonlinear equations. This requires manipulation of the equations of motion to adhere to a modular form. In this paper, a software architecture is presented for creating complex fully-coupled spacecraft simulations with a modular framework. The architecture provides a solution to these common issues seen in dynamics modeling. The modularization of the fully-coupled equations of motion is completed by solving the complex equations analytically such that the spacecraft rigid body translational and rotational accelerations are solved for first, and the other second order state derivatives are found later. This architecture is implemented in the Basilisk astrodynamics software package and is a fully tested example of the proposed software architecture.

[View Full Paper]

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AAS 18-092

A PERFORMANCE ANALYSIS OF ON-BOARD NUMERICAL PROPAGATORS

Simon Shuster,[*] David Geller[†] and Tyson Smith[‡]

On-board targeting, guidance, and navigation relies on orbit propagation algorithms that must strike a balance between accuracy and computational efficiency. To better understand this balance, the performance of numerical propagation methods is analyzed for LEO, GEO, and Molniya orbits. A numerical propagator consists of a set of differential equations describing perturbed orbital motion whose solution is approximated using a numerical integration method. This paper compares Cowell, Encke-time, Encke-beta, and Equinoctial Elements formulations over a range of integrator function evaluations for a given set of perturbations and integrators. Function evaluations are shown to be a reasonable approximation of normalized computation time. This comparison is conducted for three fixed-step integrators: a Runge-Kutta 4th order, a Nyström-Lear 4th order, and a Runge-Kutta-Butcher 6th order. Fixed-step integration ensures the amount of time for each integration step is constant, a requirement for on-board propagation. [View Full Paper]

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AAS 18-093

FLEXIBLE BASILISK ASTRODYNAMICS VISUALIZATION SOFTWARE USING THE UNITY RENDERING ENGINE

Jennifer Wood,[*] Mar Cols Margenet,[†] Patrick Kenneally,[†] Hanspeter Schaub[‡] and Scott Piggott[§]

Visualizing complex numerical simulations is a critical component of modern astrodynamics software tools. The spacecraft simulation may contain a large number of spacecraft states and simulation parameters that are more readily comprehended when presented in context in a three-dimensional visualization. Spacecraft location, orientation, and actuator states can be displayed relative to the location of celestial objects along with spacecraft configuration parameters such as size, sensor locations and orientations, or dynamic states such as flexing or slosh. Basilisk is an open-source astrodynamics simulation frame being developed by the University of Colorado Autonomous Vehicle Systems (AVS) lab and the Laboratory for Atmospheric and Space Physics (LASP). This paper presents a companion software solution which will receive a stream of Basilisk state messages and dynamically visualize these states using the Unity rendering engine. This graphics engine allows for the production of high quality visualizations without requiring the engineer to learn low-level graphics programming. The Unity integrated development environment facilitates the process of expanding or enhancing the visualization, including the creation custom simulation interface windows and view ports. [View Full Paper]

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AAS 18-094

BLACK LION: A SOFTWARE SIMULATOR FOR HETEROGENEOUS SPACEFLIGHT AND MISSION COMPONENTS

Mar Cols Margenet,* Patrick Kenneally,* Hanspeter Schaub† and Scott Piggott‡

Dynamic analysis is a validation and verification technique that involves testing, through execution or simulation of a developed product, to detect errors by analyzing responses to sets of input data. In a spaceflight context, dynamic testing addresses inspection of the binary image loaded to the spacecraft hardware as well as its behavior in response to dynamic conditions in a spacecraft operational environment. This paper describes the design and implementation of Black Lion, a purely software-based modern test environment, with the aim to perform dynamic analysis of mission spaceflight software. While this initiative is currently driven by a specific interplanetary mission, the testbed under construction is architected to be highly configurable and modular, allowing for heterogeneous software components across multiple computing platforms to be integrated into a single simulation. For example, Black Lion provides the capability to start up and run the operational command and telemetry databases, as well as the unmodified flight software executable. Virtual models are used for the ground system, the single board computer and for other required hardware components like sensors, actuators and avionics. High-fidelity dynamic, kinematic and environment models are integrated in order to test the flight software system in realistic closed-loop simulations. [View Full Paper]

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AAS 18-095

OPTIMAL MULTI-VARIABLE MULTI-CONSTRAINT SPACECRAFT GN&C REQUIREMENT DERIVATION

David C. Woffinden,[*] Sagar A. Bhatt,[†]
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Deriving spacecraft performance requirements for a guidance, navigation, and control (GN&C) system depends on the complex interaction between multiple facets. Among them include the mission concept of operations, vehicle configuration, navigation errors, maneuver execution errors, initial condition uncertainty, and disturbance torques and accelerations while ensuring the vehicle satisfies top level mission constraints such as delta-v usage or trajectory dispersion limits. This paper poses the requirement derivation process as a multiple variable, multiple constraint optimization problem and derives simultaneously the navigation requirements, maneuver execution error limits, maximum initial condition uncertainty, and allowable process noise. The approach capitalizes on concepts associated with sensitivity analysis, Monte Carlo analysis, and linear covariance analysis techniques so the optimal requirements can be derived analytically. Rather than having to resort to an iterative strategy to converge to a solution, the proposed methodology determines the optimal solution quickly in a single analytical calculation. This provides a robust, yet fast, approach for deriving GN&C requirements which accounts for the proposed trajectory design and system dynamics along with the intricate interaction between the guidance, navigation, and control subsystems. This work outlines the theoretical principles enabling this capability. Further, it demonstrates these concepts to several practical space applications including a lunar return flight segment and a lunar descent and landing scenario. Potential use for day-of-flight mission planning is introduced. [View Full Paper]

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AAS 18-096

FAST SPACECRAFT SOLAR RADIATION PRESSURE MODELING BY RAY-TRACING ON GRAPHICS PROCESSING UNIT

Patrick W. Kenneally[*] and Hanspeter Schaub[†]

A description of a method for computing on the graphics processing unit the force and torque on a spacecraft due to solar radiation pressure. The method employs ray-tracing techniques, developed in the graphics rendering discipline, to resolve spacecraft self-shadowing and self-reflections at faster than real-time computation speed. The primary algorithmic components of the ray-tracing process which contribute to the method's computational efficiency are described. These components include bounding volume hierarchy acceleration data structures, fast ray to bounding box intersection testing using the slab intersection algorithm and fast triangle intersection testing using the Möller-Trumbore algorithm. The process is implemented using C++ and OpenCL and executed on a consumer grade graphics processing unit. Initial model validation is presented comparing computed values to both the analytic cannonball model and ray traced LAGEOS II spacecraft model. A performance analysis and characterization of the effect on performance of multiple ray bounces is presented using the Mars Reconnaissance Orbiter spacecraft.

[View Full Paper]

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AAS 18-097

SATELLITE ARTICULATION TRACKING USING MONOCULAR COMPUTER VISION

David H. Curtis[*] and Richard G. Cobb[†]

Autonomous on-orbit satellite servicing and inspection benefits from an inspector satellite that can track the motion of a primary satellite, including the motion of appendages such as solar arrays, antennas, and sensors. This paper presents a method of estimating the articulation parameters and shape of a satellite using resolved monocular imagery. A simulated point cloud representing a nominal satellite with articulating solar panels and a complex articulating appendage is developed and projected to the image coordinates that would be seen from an inspector following a given inspection route. A previously developed model is used to initialize an extended Kalman filter to track the satellite's motion and articulation from the image coordinates. [View Full Paper]

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AAS 18-098

NEW METHODOLOGY FOR WIND MODELLING FOR LAUNCHER APPLICATION

Martine Ganet-Schoeller,[*] Vincent Feuillard,[†] Jean Desmariaux[‡] and Benoît Mazellier[§]

This paper focusses on co-founded Ariane Group and CNES research activities, performed with the support of Airbus Group Innovation (AGI), for developing enhanced wind model to improve the design and validation of launcher control during its ascent phase. During launcher ascent phase, the wind is the most critical perturbation that could lead to dramatic loads, therefore, vehicle's response to atmospheric disturbances, especially wind, must be carefully evaluated to ensure that its design will allow it to meet its operational requirements. The purpose of this study was to develop an enhanced model applicable both for control design and for validation, using last development of stochastic modeling tools. We propose in this paper, a new methodology based on non-stationary data transformation and data clustering for modelling wind perturbation during launcher ascent phase. The main advantage of this method is that we use a data transformation into non stationary Gaussian process which encompasses restricting hypothesis taken for traditional Dryden model definition. Open loop accuracy and closed loop representativeness of both methods were compared on control quantity of interest showing the excellent performance of data transformation model. We henceforth have a simple and efficient tool that could generate easily wind perturbation model for launcher control design and validation using different database (launch pad, monthly dependency) and various conditions or trajectory. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL HARDWARE

Session 10

National Chairperson:

Mark Jackson, Blue Origin

Local Chairpersons:

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Tomas Ryan, Ball Aerospace & Technologies Corp.

The following paper numbers were not assigned:

AAS 18-109 to -110

AAS 18-101

A NEW DOMESTIC SOURCE FOR HIGH PERFORMANCE STAR TRACKERS: THE BALL CT2020

E. Tchilian*

Recent advances in detector technology, optics and electronics architecture allow for a compact, high performance star tracking at a competitive price point while using all domestically sourced components from trusted suppliers. Ball Aerospace is proud to introduce the advanced CT2020 star tracker featuring a new state of the art CMOS detector with exceptional radiation tolerance and performance. The compact and fully integrated design of the CT2020 does not require an external electronics unit or extra cabling while also allowing for expanded operational envelope with the use of a 15 deg Sun exclusion shade. Leveraging flight proven High Accuracy Star Tracker (HAST) image processing, the CT2020 can achieve single head accuracies in the realm of 1 arc-second autonomous attitude output (total error RMS), while also allowing for customer driven "directed search" mode for even higher accuracy. With a HAST like logic, performance is retained across a large dynamic envelope. Modular software architecture allows for space situational awareness capability as well as on-orbit upgradability and re-calibration to retain performance at end of life. Notably, the CT2020 contains built in on-orbit environment simulator with hardware in the loop to allow for efficient spacecraft integration and operational simulation. This paper discusses the optimization technique used to derive the star tracker architecture as well as advances in detector, optics and electronics technologies used in the CT2020. We discuss how the CT2020 architecture enables high accuracy attitude determination at a lower price point. [View Full Paper]

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AAS 18-102

HIGH PERFORMANCE REACTION WHEELS

Eric Stromswold,[*] Jim Krebs,[†] Bob Sullivan[‡] and Steve Fox[§]

Reaction Wheels (RWs) are a proven method of attitude control for satellites and spacecraft. Cayuga Astronautics is developing two families of RWs. The smaller RW family has an OD of 203 mm (8 inch) and is available in 6 different momentum-torque combinations ranging from 2.5 to 16 Nms of momentum with torques ranging from 0.97 to 0.15 Nm respectively. The larger RW has an OD of 305 mm (12 inch) and is available in 6 different momentum-torque combinations ranging from 16 to 110 Nms of momentum with torques ranging from 4.8 to 0.8 Nm respectively. As such they will be the most powerful RWs on the market in their respective sizes and will offer spacecraft agility that is currently only possible with thrusters or Control Moment Gyros (CMGs).

Both families of RWs feature a custom ironless armature radial gap motor integrated into the flywheel rim. The design of the motor results in zero motor cogging, produces significant size and weight savings, and results in low power and drag. Size, weight and cost are also minimized by keeping part count to a minimum. Both RW families feature robust hybrid bearings that are immune to the failure mechanism that crippled a number of in-flight RWs in recent years. [View Full Paper]

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AAS 18-103

ATTITUDE CONTROL SYSTEM COMPLEXITY REDUCTION VIA TAILORED VISCOELASTIC DAMPING CO-DESIGN*

Chendi Lin,† Daniel R. Herber,‡ Vedant,§ Yong Hoon Lee,†
Alexander Ghosh,§ Randy H. Ewoldt† and James T. Allison‡

Intelligent structures utilize distributed actuation, such as piezoelectric strain actuators, to control flexible structure vibration and motion. A new type of intelligent structure has been introduced recently for precision spacecraft attitude control. It utilizes lead zirconate titanate (PZT) piezoelectric actuators bonded to solar arrays (SAs), and bends SAs to use inertial coupling for small-amplitude, high-precision attitude control and active damping. Integrated physical and control system design studies have been performed to investigate performance capabilities and to generate design insights for this new class of attitude control system. Both distributed- and lumped-parameter models have been developed for these design studies. While PZTs can operate at high frequency, relying on active damping alone to manage all vibration requires high-performance control hardware. In this article we investigate the potential value of introducing tailored distributed viscoelastic materials within SAs as a strategy to manage higher-frequency vibration passively, reducing spillover and complementing active control. A case study based on a pseudo-rigid body dynamic model (PRBDM) and linear viscoelasticity is presented. The tradeoffs between control system complexity, passive damping behavior, and overall dynamic performance are quantified.

[View Full Paper]

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AAS 18-104

HYDRA STAR TRACKER FOR JUICE MISSION

Benoît Gelin,* Guillaume Montay, Yannick Henriquel, Jean-Frédérick Bouvry, Pascal Regnier† and Daniele Gherardi‡

The Jupiter Icy Moon Explorer (JUICE) is an ESA mission whose aim is to study the Jovian system; Jupiter itself, its moons (Europa, Ganymede and Callisto) and the magnetosphere. The mission profile imposes considerable radiation constraints on the spacecraft, which are uncommon in typical space programs due to the Jupiter magnetic moment which is the largest of the solar system (over 10 000 times more than the Earth). It results in a high total dose exposure at electronic parts level (factor ten with regard to typical GEO missions), high number of Single Event Effects and internal charging effects.

For this challenging mission, Sodern has been selected to provide a specific version of HYDRA star tracker. HYDRA is the multiple head CMOS Active Pixel Sensor (APS) star tracker developed by Sodern and it has achieved TRL-9 after being launched successfully aboard the French Spot-6 Earth observation satellite on September 9th 2012. HYDRA is composed of two physical units, Electronic Units (EU) for communication management, power supply and attitude computation, and Optical Heads (OH) for image acquisition and video pre-processing. This architecture allows protecting the Electrical Units by the spacecraft internal shielding while the Optical Heads are outside. The configuration chosen for JUICE is two EU (one in cold redundancy) and three OH.

A first analysis has been already performed in the scope of precursor activities to assess the suitability of HYDRA Star Tracker to the intense radiation environment of the JUICE mission. Since this analysis, the worst case radiation environment specified for JUICE mission has been severely degraded, by a factor 7 for proton flux and by a factor 6 for electrons flux, leading to conditions 150 times harsher than geostationary orbit worst case. This has put into question some of the previously identified adaptations of HYDRA.

In this paper Sodern presents the complementary analysis performed since this specification modification. Apart from some local optimization of shielding thickness, only a few algorithms improvements are necessary to robustify HYDRA and make it suitable to this even more constraining environment. [View Full Paper]

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AAS 18-105

RATE MEASUREMENT UNIT FOR ATTITUDE DETERMINATION AND CONTROL SUBSYSTEM

Jose Beitia[*] and Steeve Kowaltschek[†]

Over the past 50 years, many different gyro technologies have been developed and used in space, with Fiber Optical Gyros (FOG), Ring Laser Gyros (RLG) and Hemispherical Resonator Gyros (HRG) being predominantly used from the late '90s up to today. Each technology offers a wide range of advantages and disadvantages while most of the time offering a similar performance. More recently, new applications have emerged in the commercial industry for which accuracy and precision are no longer the driving factors. Instead, reliability, mass, power budgets, and meeting performance at reduced cost and size have become paramount.

In that context, InnaLabs has developed a Coriolis Vibratory Gyroscope (CVG) sharing common features with HRG, and, with the support of the European Space Agency, a 3-axis Rad-Hard Rate Measurement Unit (RMU) named ARIETIS is now being developed by InnaLabs to address Earth Observation applications in Low-Earth Orbit (LEO), Navigation in Medium-Earth Orbit (MEO), and AOCS in Geostationary Orbit (GEO) with lifetime of more than 15 years. After a brief description of the InnaLabs CVG basic principles and an overview of the CVG technical strengths in comparison to competing for available technologies, this paper describes the key features and budgets of ARIETIS, it's design, construction and operating principles, with a special emphasis on the targeted end-of-life performance. [View Full Paper]

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BCT ADVANCING GN&C HARDWARE WITH THE RW4& RW8 REACTION WHEELS

Matthew Baumgart, Matt Carton, Daniel Hegel, Chris Messick, Bryce Peters, Steve Schneider and Stephen Steg*

The Blue Canyon Technologies (BCT) Reaction Wheel Assembly (RWA) is a reliable, high performance Reaction Wheel, compatible with a variety of spacecraft configurations and missions. BCT offers multiple RWA sizes to support a range of Spacecraft inertias. In cooperation with a Defense Production Act (DPA) Title III project, BCT has expanded the RWA product line with a flight-qualified design, in the 4 Nms to 8 Nms momentum range, providing low to mid-level momentum storage capacity in support of smaller satellite systems with 5 to 10-year mission lives. BCT developed the RW4 & RW8 wheel design by leveraging a proven design, manufacturing, and test approach from the smaller RWA product line where product performance and price are the major drivers. The RW4 and RW8 reaction wheels are a high-performance, low-cost, high-reliability Reaction Wheels which can be readily manufactured in response to Space Mission needs supporting Civil, NASA, Commercial, and DoD satellites. This paper reviews the RW4 & RW8 design, configuration options, and performance capabilities to support various missions. [View Full Paper]

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AAS 18-107

ASTRO-XP HIGH ACCURACY STAR TRACKER

U. Schmidt* and B. Pradarutti†

The present generation of APS based star trackers is targeted as generic attitude determination sensors in order to cover a wide range of missions such like geo-telecom, Earth observation and constellations. They have performances typically in the range of 1…3arcsec 1sigma. Although this is easily sufficient for most missions, there exist a range of missions requiring significantly higher performance. For these high accuracy demanding missions, the AOCS design will usually attempt to develop a fine guidance sensor embedded in the payload itself in order to provide this higher measurement performance. However, this is frequently not possible either due to the payload characteristics or observation targets such like planetary surfaces. In these cases a separate high performance star tracker, mounted on the optical bench, is required. Jena-Optronik GmbH received a pre-development contract from ESA to design a prototype of a high ac-curacy star tracker optical head. The pre-development will be continued with a full EM and qualification approach. This new product enhances the Jena-Optronik GmbH ASTRO-series star tracker family towards an utmost high performance star tracker. Such a high accuracy star tracker must be compatible with the optical bench environment. As such it needs a small footprint, low power dissipation and high thermal stability over a wide operational temperature range. Therefore, the architectural design is split in an optical head and an electronics unit. In order to achieve the required high accuracy special attention has been paid to the optics, detector and thermal design but also to the electronics and software layout. [View Full Paper]

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AAS 18-108

ATOM INTERFEROMETRY: LOCKHEED MARTIN SYSTEMS DEVELOPMENT

Hugh F. Rice,[*] Vincent Benischek[*] and Les Sczaniecki[†]

The maturity of Atomic Interferometry from laboratory science, based on Nobel Prize level Physics, to potential product insertion into Precision Navigation and Timing applications has been a 20 year journey. Lockheed Martin has been working with the Atom Interferometric technology development teams and evaluating potential applications of Atom Interferometric sensors for > 15 years. Technology insertion of high precision sensors, into tactical programs, e.g.: Ring Laser Gyros replacing mechanical gyros, was slow to happen and required extensive sensor development and qualification, corporate systems integration, and both government and private company investment. Atom Interferometric sensors now are at that stage where discussion of technology insertion, in the fields of inertial sensing (gyroscopes and accelerometers) gravity sensing (gravimeters and gradiometers), and precision timing, can be considered.

This paper presents overviews of Atom Interferometric (AI) theory, AI inertial sensors and gravity sensors. This paper will also discuss the application of AI gravity sensors for navigation system aiding independent of GPS and DNC chart enhancement. Information developed from the gravity signature can be a significant contributor to battle space situational awareness, providing enhanced knowledge of the local operating environment and of the location of each operational participant in that environment.

The first moving base gravity gradient measuring system was developed by Lockheed Martin (circa 1990). This system was designed to precisely measure the full tensor gravity gradient field. This system was successfully used to correct an inertial navigator for gravity induced error, apply gravity techniques to bound INS errors and demonstrate gravity based collision avoidance.

Lockheed Martin began working with Stanford University, and AOSense (2005-07), a Stanford University spin off, to investigate the potential of atomic interferometry to be the technology foundation for the next generation, low cost gravity sensor system. Lockheed Martin funded AOSense in 2011 to build the first commercial gravimeter based on atom interferometric technologies and also funded upgrades in 2015. [View Full Paper]

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SCIENCE WEATHER ENABLED

Session 11

National Chairperson:

Bill Frazier, NASA Jet Propulsion Laboratory

Local Chairpersons:

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Tim Bevacqua, Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 18-118 to -120

AAS 18-111

ON-ORBIT VERIFICATION OF GMI INSTRUMENT SPIN BALANCE STABILITY PERFORMANCE TO ENABLE ESSENTIAL WEATHER FORECASTING

Laoucet Ayari,[*] Michael Kubitschek,[*] Gunnar Ashton,[*] Steve Johnston,[*] Dave Debevec,[*] David Newell[*] and Joseph Pellicciotti[†]

The Global Microwave Imager (GMI) instrument must spin at a constant rate of 32 rpm continuously for the 3-year mission life. Therefore, GMI must be very precisely balanced about the spin axis and CG to maintain stable scan pointing and to minimize disturbances imparted to the spacecraft and attitude control on-orbit. The GMI instrument is part of the core Global Precipitation Measurement (GPM) spacecraft and is used to make calibrated radiometric measurements at multiple microwave frequencies and polarizations. The GPM mission is an international effort managed by the National Aeronautics and Space Administration (NASA) to improve climate, weather, and hydro-meteorological predictions through more accurate and frequent precipitation measurements. Ball Aerospace and Technologies Corporation (BATC) was selected by NASA Goddard Space Flight Center to design, build, and test the GMI instrument. The GMI design has to meet a challenging set of spin balance requirements and had to be brought into simultaneous static and dynamic spin balance after the entire instrument was already assembled and before environmental tests began. On-orbit attitude control data validated ground test data, easily achieving the program requirement with considerable margin to spare. The focus of this contribution is on the analytical and test activities undertaken to meet the challenging spin balance requirements of the GMI instrument. The novel process of measuring the residual static and dynamic imbalances with a very high level of accuracy and precision is presented together with the prediction of the optimal balance masses and their locations. [View Full Paper]

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GOES-16 ABI ON-ORBIT INR TUNING AND PERFORMANCE

**Daniel D. Gall,[*] Vincent Virgilio,[†] Richard Forkert,[‡]
John Van Naarden,[§] and Paul C. Griffith[**]**

The Geostationary Operational Environmental Satellite 16 (GOES-16) initiated a new era in U.S. geostationary weather and environmental observations, with the Advanced Baseline Imager (ABI) as the satellite's primary instrument for capturing images of Earth's weather, climate, oceans, and environment. ABI delivers not only significant improvements in spectral, spatial, and temporal resolution, but also exceptional geolocation performance through an advanced system for image navigation and registration (INR). INR performance is the same for any sized image regardless of the image content.

Unlike previous instruments, ABI INR performance relies on precise line-of-sight (LOS) knowledge, not on absolute pointing accuracy. Ground processing recursively filters measurements from the GOES-16 spacecraft's guidance, navigation, and control subsystem telemetry (orbit, attitude, and angular rates), ABI scan encoders, and ABI star observations through a Kalman filter to accurately predict the LOS for every detector sample downlinked. By periodically observing stars, ABI effectively functions as its own star tracker, enabling the ground processing to accurately estimate end-to-end LOS attitude and thermal drift. In addition, interleaved visible and infrared star collections allow direct coregistration between the three ABI focal planes.

Activities performed during GOES-16 post launch testing of ABI to tune the INR performance, specifically the star measurement and Kalman filter performance, are presented along with the measured on-orbit INR performance for the calibrated, navigated, and resampled ABI pixel images. [View Full Paper]

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AAS 18-113

IMAGING X-RAY POLARIMETRY EXPLORER MISSION ATTITUDE DETERMINATION AND CONTROL CONCEPT

Jeff Bladt,[*] William D. Deininger,[†] William Kalinowski,[‡] Mary Boysen,[§] Kyle Bygott,[**] Larry Guy,[††] Christina Pentz,[‡‡] Chris Seckar,[§§] John Valdez,[***] Jeffrey Wedmore,[†††] Brian Ramsey,[‡‡‡] Stephen L. O'Dell,[§§§] and Allyn Tennant[****]

The goal of the Imaging X-Ray Polarimetry Explorer (IXPE) Mission is to expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." X-ray polarimetry is the focus of the IXPE science mission. Polarimetry uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise measurable. The IXPE Observatory consists of Space craft and Payload modules. The Payload includes three polarization sensitive, X-ray detector units (DU), each paired with its corresponding grazing incidence mirror module assemblies (MMA). A deployable boom provides the correct separation (focal length) between the DUs and MMAs. These Payload elements are supported by the IXPE Spacecraft. A star tracker is mounted directly with the deployed Payload to minimize alignment errors between the star tracker line of sight (LoS) and Payload LoS. Stringent pointing requirements coupled with a flexible structure and a non-collocated attitude sensor-actuator configuration requires a thorough analysis of control-structure interactions. A non-minimum phase notch filter supports robust control loop stability margins. This paper summarizes the IXPE mission science objectives and Observatory concepts, and then it describes IXPE attitude determination and control implementation. IXPE LoS pointing accuracy, control loop stability, and angular momentum management are discussed. [View Full Paper]

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AAS 18-114

OPTICAL AUTOCOVARIANCE WIND LIDAR FOR GUIDANCE, NAVIGATION, AND CONTROL

S. Tucker, M. Adkins, R. Narciso, J. Applegate, N. Siegel, M. Conde, G. Taudien, P. Kaptchen, J. Marquardt, I. Gravseth and C. Weimer*

This paper briefly describes the Optical Autocovariance Wind Lidar technology, reviews the technology demonstrations and validation efforts to date, and discusses the ways in which the fields of guidance, navigation, and control (GNC) and Doppler wind lidar (DWL) have been mutually beneficial. [View Full Paper]

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AAS 18-115

PRELIMINARY SATURN ATMOSPHERIC DENSITY RESULTS FROM CASSINI'S FINAL PLUNGE

Dylan R. Boone,[*] Mau Wong,[†] Julie Bellerose[‡] and Duane Roth[§]

The Cassini spacecraft descended into the planet Saturn on September 15, 2017, capping a twenty year mission full of scientific discoveries. The high-gain antenna was held on Earth-point until torques from atmospheric drag caused the spacecraft to lose line-of-sight lock with Earth. The Doppler data collected during the final plunge contains information about the spacecraft's acceleration due to atmospheric drag, and therefore, the density of Saturn's atmosphere. In this work, we present preliminary analysis of the end of mission Doppler data and its implications regarding the density of Saturn's upper atmosphere. A reconstruction of the spacecraft's final trajectory is discussed and used to fit a model of Saturn's atmosphere to the Doppler data taken during the final plunge. The Cassini navigation team's experience flying the spacecraft through the final five low altitude Saturn periapses is also discussed in the context of atmospheric drag and density models. [View Full Paper]

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AAS 18-116

JPSS-1: BUILDING THE NATION'S NEXT GENERATION OPERATIONAL POLAR-ORBITING WEATHER SATELLITE

Scott C. Asbury*

The Joint Polar Satellite System – 1 (JPSS-1) is the Unites States' next-generation, operational, polar-orbiting weather satellite that was launched on November 18, 2017 and subsequently renamed NOAA-20. The JPSS-1 satellite is comprised of the spacecraft bus and its five instrument payloads. Ball Aerospace built the JPSS-1 spacecraft bus, the Ozone Mapping and Profiler Suite (OMPS) instrument, and was the satellite integrator. This paper provides an overview of the JPSS program, the design and construction of the satellite bus, integration of the instruments, satellite-level test program, and the launch campaign. [View Full Paper]

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AAS 18-117

NOVEL SPACECRAFT RECOVERY, GUIDANCE AND CONTROL TO ENABLE KEPLER SCIENCE MISSION CONTINUATION

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The Kepler spacecraft has completed more than three years and 15 science campaigns in its repurposed K2 mission. Using the two remaining reaction wheels and precise thruster pulses for control, the photometer studies fields of view in the ecliptic plane for up to 85 days at a time to find exoplanets, study stellar astrophysics and enable a community driven science program. The hydrazine fuel used for attitude control and momentum management is the most life-limiting consumable on the spacecraft. This paper will discuss ongoing operational efforts to minimize fuel consumption and maximize on-orbit lifetime. Recently, a safe mode control scheme utilizing only the two remaining reaction wheels was deployed on the vehicle. In the event of a fault, the spacecraft will enter and dwell in a power positive, safe state without using any fuel. This two wheel safe mode replaces thruster controlled safe mode which had the highest fuel burn rate of any K2 operational mode. Fuel consumption and thruster performance tracking have become paramount in the latter stages of the K2 mission. To improve insight into fuel consumption and thruster performance, new methodologies to analyze the unique thruster operations and monitor for end of life indicators have been developed. Predicting fuel exhaustion is critical to ensuring enough fuel is left in the tank to download the final science data from the vehicle. These on-orbit changes and ground analyses have resulted in the most recent science campaigns being the most fuel efficient campaigns in K2. [View Full Paper]

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PIONEERS OF GUIDANCE, NAVIGATION AND CONTROL AND ASTRODYNAMICS

Session 12

National Chairperson:

Neil Dennehy, NASA Goddard Space Flight Center

Local Chairperson:

James McQuerry, Ball Aerospace & Technologies Corp. (Retired)

The following papers were not available for publication:

AAS 18-125 (Presentation Only)

The following paper numbers were not assigned:

AAS 18-128 to -130

AAS 18-121

HOW DOC DRAPER BECAME THE FATHER OF INERTIAL GUIDANCE

Philip D. Hattis*

With Missouri roots, a Stanford Psychology degree, and a variety of MIT degrees, Charles Stark "Doc" Draper formulated the basis for reliable and accurate gyro-based sensing technology that enabled the first and many subsequent inertial navigation systems. Working with colleagues and students, he created an Instrumentation Laboratory that developed bombsights that changed the balance of World War II in the Pacific. His engineering teams then went on to develop ever smaller and more accurate inertial navigation for aircraft, submarines, strategic missiles, and spaceflight. The resulting inertial navigation systems enable national security, took humans to the Moon, and continue to find new applications. This paper discusses the history of Draper's path to becoming known as the "Father of Inertial Guidance." [View Full Paper]

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AAS 18-122

HENRY HOFFMAN: NASA'S SATELLITE DOCTOR

James R. O'Donnell[*] and Cornelius J. Dennehy[†]

In this paper, the authors will describe the career and technical contributions of one of NASA's recognized Guidance, Navigation and Control (GN&C) "Pioneers:" Mr. Henry Hoffman, also known as NASA's "Satellite Doctor." In addition to summarizing his formative early career experiences at the Naval Ordnance Laboratory (NOL) developing the guidance and control system for the Navy's SUBmarine ROCket (SUBROC) anti-submarine missile, this paper will also touch on Mr. Hoffman's contributions to NASA's early spacecraft developments at the very dawn of the space age. In a walkthrough of Henry's history of spacecraft GN&C engineering from the 1960s and the 1970s, we have strived to provide in this paper several interesting insights into the design and operation of several of NASA Goddard Space Flight Center's (GSFC) early scientific satellites. This paper will focus primarily on Mr. Hoffman's noteworthy direct contributions to the safe recovery and restored operation of several scientific spacecraft, among them the first Tracking and Data Relay Satellite System (TDRSS-1), the Solar Maximum Mission (SMM) spacecraft, the joint NASA/ESA Ulysses spacecraft, the first of a new generation of Geosynchronous Orbit Environmental Satellites (GOES) meteorological spacecraft, and the joint ESA/NASA SOlar Heliospheric Observatory (SOHO) spacecraft. This paper will conclude with a summary of several fundamental "rules of thumb," or what we typically call today "Lessons Learned," which Mr. Hoffman formulated from some of the real-world spacecraft experiences that occurred over the course of his six-decade-long career in the field of spacecraft GN&C engineering. The authors believe Mr. Hoffman would be very pleased that his GN&C "rules of thumb" are being shared here with the reader in the hope they may be of some practical value in their GN&C work.

[View Full Paper]

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AAS 18-123

ASTRODYNAMICS PIONEER: ROBERT FARQUHAR

Kathleen C. Howell[*] and David C. Folta[†]

Dr. Robert Farquhar was very active throughout his career in flight dynamics and mission design. Early on, he recognized the potential of the libration points such that leveraging the dynamical pathways in their vicinity could open new mission options. The study of spacecraft oscillating about the Earth-Moon translunar L_2 libration point for a communications satellite to service the back-side of the Moon led to the concept of halo orbits. The concept became reality with the eventual launch of ISEE-3 in 1978 and the subsequent insertion of the satellite into an orbit about the Sun-Earth L_1 libration point.

[View Full Paper]

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AAS 18-124

DR. BRADFORD W. PARKINSON: THE FATHER OF GPS

Frank H. Bauer*

Of all the Guidance, Navigation & Control innovations, none can compare with the revolutionary impact that the Global Positioning System (GPS) has had to society. Nearly everyone benefits from this navigation and timing marvel. GPS has transformed all modes of transportation, enabling safer journeys. It supports the world's critical infrastructure, including the electric grid, banking systems, stock exchanges and cell phone networks. To date, billions of GPS receivers are embedded in cell phones and a myriad of mobile and fixed devices. GPS would not have been realized without the leadership, vision, and tenacity of Dr. Bradford (Brad) Parkinson, a true Guidance, Navigation and Control pioneer. This GN&C Pioneers paper chronicles Dr. Parkinson's background, the challenges he encountered to bring GPS to the forefront and how he overcame those challenges. It also conveys how, as a Stanford professor, Parkinson was able to transform GPS use into the multi-faceted utility, touching every industry and nearly every person on Earth. It will conclude with Parkinson's current efforts to ensure that GPS and its international cousins are available and protected from signal jamming or spoofing threats, to ensure that society can trust that this critical utility is available and accurate now and in the future. [View Full Paper]

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NGUYEN XUAN VINH – A LIFE IN HYPERSONIC FLIGHT*

Aron A. Wolf,† Daniel J. Scheeres‡ and Ping Lu§

Nguyễn Xuân Vinh (born January 1930 in Yên Bái, Vietnam) is a noted Vietnamese-American aerospace scientist and educator whose seminal work on the guidance, dynamics and optimal control of space vehicles and their interaction with the atmosphere has played a fundamental role in space exploration. Vinh is Professor Emeritus of Aerospace Engineering at the University of Michigan, where he taught for nearly thirty years. Among his many publications was "Hypersonic and Planetary Entry Flight Mechanics" (1980. Vinh, N. X.; Busemann, A.; Culp, R. D. University of Michigan Press) which contains equations for hypersonic flight that came to be known as "the Vinh equations."

[View Full Paper]

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AAS 18-127

INNOVATION EXPERIENCES FROM VANGUARD, EXPLORER 1, SIDEWINDER, AND NOTSNIK

John L. Goodman*

This paper explores the innovation experiences and challenges from three satellite programs and one missile program in the 1950s. Project Vanguard, with Milton "Milt" W. Rosen of the Naval Research Laboratory (NRL) serving as Technical Director, launched three satellites during the International Geophysical Year (IGY, 1957-1958). Dr. James Van Allen and his team of graduate students at the University of Iowa developed satellite instruments in record time leading to the launch of Explorer I and the later discovery of the Van Allen radiation belts. Dr. William "Bill" McLean led a team at the Naval Ordnance Test Station (NOTS) at China Lake, California that developed the Sidewinder air-to-air missile from 1947-1956, and in 1958 made six attempts to launch a satellite called NOTSNIK. [View Full Paper]

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SPACE LAUNCH SYSTEM (SLS) NAVIGATION

Session 13

National Chairpersons:

Evan Anzalone, NASA Marshall Space Flight Center

Ted Oliver, NASA Marshall Space Flight Center

Local Chairpersons:

Heidi Hallowell, Ball Aerospace & Technologies Corp.

John Reed, United Launch Alliance

The following paper numbers were not assigned:

AAS 18-138 to -140

AAS 18-131

SLS MODEL BASED DESIGN: A NAVIGATION PERSPECTIVE

T. Emerson Oliver,* Evan Anzalone,† Thomas Park‡ and Kevin Geohagan§

The SLS Program has implemented a Model-based Design (MBD) and Model-based Requirements approach for managing component design information and system requirements. This approach differs from previous large-scale design efforts at Marshall Space Flight Center where design documentation alone conveyed information required for vehicle design and analysis and where extensive requirements sets were used to scope and constrain the design. The SLS Navigation Team is responsible for the Program-controlled Design Math Models (DMMs) which describe and represent the performance of the Inertial Navigation System (INS) and the Rate Gyro Assemblies (RGAs) used by Guidance, Navigation, and Controls (GN&C). The SLS Navigation Team is also responsible for navigation algorithms. The navigation algorithms are delivered for implementation on the flight hardware as a DMM. For the SLS Block 1B design, the additional GPS Receiver hardware model is managed as a DMM at the vehicle design level. This paper describes the models, and discusses the processes and methods used to engineer, design, and coordinate engineering trades and performance assessments using SLS practices as applied to the GN&C system, with a particular focus on the navigation components.

[View Full Paper]

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AAS 18-132

6DOF TESTING OF THE SLS INERTIAL NAVIGATION UNIT

Kevin W. Geohagan,[*] William P. Bernard,[†] T. Emerson Oliver,[‡] Dennis J. Strickland[§] and Jared O. Leggett[**]

The Navigation System on the NASA Space Launch System (SLS) Block 1 vehicle performs initial alignment of the Inertial Navigation System (INS) navigation frame through gyrocompass alignment (GCA). In lieu of direct testing of GCA accuracy in support of requirement verification, the SLS Navigation Team proposed and conducted an engineering test to, among other things, validate the GCA performance and overall behavior of the SLS INS model through comparison with test data.

This paper will detail dynamic hardware testing of the SLS INS, conducted by the SLS Navigation Team at Marshall Space Flight Center's 6DOF Table Facility, in support of GCA performance characterization and INS model validation. A 6-DOF motion platform was used to produce 6DOF pad twist and sway dynamics while a simulated SLS flight computer communicated with the INS. Tests conducted include an evaluation of GCA algorithm robustness to increasingly dynamic pad environments, an examination of GCA algorithm stability and accuracy over long durations, and a long-duration static test to gather enough data for Allan Variance analysis. Test setup, execution, and data analysis will be discussed, including analysis performed in support of SLS INS model validation.

[View Full Paper]

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AAS 18-133

SENSOR DATA QUALITY AND ANGULAR RATE DOWN-SELECTION ALGORITHMS ON SLS EM-1

Thomas Park,[*] Emerson Oliver[†] and Austin Smith[‡]

The NASA Space Launch System Block 1 launch vehicle is equipped with an Inertial Navigation System (INS) and multiple Rate Gyro Assemblies (RGA) that are used in the Guidance, Navigation, and Control (GN&C) algorithms. The INS provides the inertial position, velocity, and attitude of the vehicle along with both angular rate and specific force measurements. Additionally, multiple sets of co-located rate gyros supply angular rate data. The collection of angular rate data, taken along the launch vehicle, is used to separate out vehicle motion from flexible body dynamics. Since the system architecture uses redundant sensors, the capability was developed to evaluate the health (or validity) of the independent measurements. A suite of Sensor Data Quality (SDQ) algorithms is responsible for assessing the angular rate data from the redundant sensors. When failures are detected, SDQ will take the appropriate action and disqualify or remove faulted sensors from forward processing. Additionally, the SDQ algorithms contain logic for down-selecting the angular rate data used by the GN&C software from the set of healthy measurements. This paper provides an overview of the algorithms used for both fault-detection and measurement down selection. [View Full Paper]

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AAS 18-134

OPTIMIZATION OF SECOND FAULT DETECTION THRESHOLDS TO MAXIMIZE MISSION PROBABILITY OF SUCCESS

Evan J. Anzalone[*]

In order to support manned spaceflight safety requirements, the Space Launch System (SLS) has defined program-level requirements for key systems to ensure successful operation under single fault conditions. The SLS program has also levied requirements relating to the capability of the Inertial Navigation System to detect a second fault. This detection functionality is required in order to feed abort analysis and ensure crew safety. Increases in navigation state error due to sensor faults in a purely inertial system can drive the vehicle outside of its operational as-designed environmental and performance envelope. As this performance outside of first fault detections is defined and controlled at the vehicle level, it allows for the use of system level margins to increase probability of mission success on the operational edges of the design. A top-down approach is utilized to assess vehicle sensitivity to second sensor faults. A wide range of failure scenarios in terms of both fault magnitude and time is used for assessment. The approach also utilizes a schedule to change fault detection thresholds autonomously. These individual values are optimized along a nominal trajectory in order to maximize probability of mission success in terms of system-level insertion requirements while minimizing the probability of false positives. This paper will describe an approach integrating Genetic Algorithms and Monte Carlo analysis to tune the threshold parameters to maximize vehicle resilience to second fault events over an ascent mission profile. The analysis approach and performance assessment and verification will be presented to demonstrate the applicability of this approach to second fault detection optimization to maximize mission probability of success through taking advantage of existing margin. [View Full Paper]

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AAS 18-135

SPACE LAUNCH SYSTEMS BLOCK 1B PRELIMINARY NAVIGATION SYSTEM DESIGN

T. Emerson Oliver,[*] Thomas Park,[†] Evan Anzalone,[‡] Austin Smith,[§] Dennis Strickland[**] and Sean Patrick[††]

NASA is currently building the Space Launch Systems (SLS) Block 1 launch vehicle for the Exploration Mission 1 (EM-1) test flight. In parallel, NASA is also designing the Block 1B launch vehicle. The Block 1B vehicle is an evolution of the Block 1 vehicle and extends the capability of the NASA launch vehicle. This evolution replaces the Interim Cryogenic Propulsive Stage (ICPS) with the Exploration Upper Stage (EUS). As the vehicle evolves to provide greater lift capability, increased robustness for manned missions, and the capability to execute more demanding missions so must the SLS Integrated Navigation Sys-tem evolved to support those missions. This paper describes the preliminary navigation systems design for the SLS Block 1B vehicle. The evolution of the navigation hardware and algorithms from an inertial-only navigation system for Block 1 ascent flight to a tightly coupled GPS-aided inertial navigation system for Block 1B is described. The Block 1 GN&C system has been designed to meet a LEO insertion target with a specified accuracy. The Block 1B vehicle navigation system is designed to support the Block 1 LEO target accuracy as well as trans-lunar or trans-planetary injection accuracy. Additionally, the Block 1B vehicle is designed to support human exploration and thus is designed to minimize the probability of Loss of Crew (LOC) through high-quality inertial instruments and robust algorithm design, including Fault Detection, Isolation, and Recovery (FDIR) logic. [View Full Paper]

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POWERED EXPLICIT GUIDANCE MODIFICATIONS & ENHANCEMENTS FOR SPACE LAUNCH SYSTEM BLOCK-1 AND BLOCK-1B VEHICLES

Paul Von der Porten,[*] Naeem Ahmad,[*] Matt Hawkins[†] and Thomas Fill[‡]

NASA is currently building the Space Launch System (SLS) Block-1 launch vehicle for the Exploration Mission 1 (EM-1) test flight. NASA is also currently designing the next evolution of SLS, the Block-1B. The Block-1 and Block-1B vehicles will use the Powered Explicit Guidance (PEG) algorithm (of Space Shuttle heritage) for closed loop guidance. To accommodate vehicle capabilities and design for future evolutions of SLS, modifications were made to PEG for Block-1 to handle multi-phase burns, provide PEG updated propulsion information, and react to a core stage engine out. In addition, due to the relatively low thrust-to-weight ratio of the Exploration Upper Stage (EUS) and EUS carrying out Lunar Vicinity and Earth Escape missions, certain enhancements to the Block-1 PEG algorithm are needed to perform Block-1B missions to account for long burn arcs and target translunar and hyperbolic orbits. This paper describes the design and implementation of modifications to the Block-1 PEG algorithm as compared to Space Shuttle. Furthermore, this paper illustrates challenges posed by the Block-1B vehicle and the required PEG enhancements. These improvements make PEG capable for use on the SLS Block-1B vehicle as part of the Guidance, Navigation, and Control (GN&C) System.

[View Full Paper]

[*] Aerospace Engineer, EV42/Guidance, Navigation, and Mission Analysis Branch, NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA.

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AAS 18-137

ASSESSMENT AND VERIFICATION OF SLS BLOCK 1B EXPLORATION UPPER STAGE AND STAGE DISPOSAL PERFORMANCE

Sean Patrick,[*] T. Emerson Oliver[†] and Evan J. Anzalone[‡]

Delta-v allocation to correct for insertion errors caused by state uncertainty is one of the key performance requirements imposed on the SLS Navigation Sys-tem. Additionally, SLS mission requirements include the need for the Exploration Upper Stage (EUS) to be disposed of successfully. To assess these requirements, the SLS navigation team has developed and implemented a series of analysis methods. Here the authors detail the Delta-Delta-V approach to assessing delta-v allocation as well as the EUS disposal optimization approach. [View Full Paper]

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ADVANCES IN RENDEZVOUS, PROXIMITY OPERATIONS AND DOCKING (RPOD)

Session 14

National Chairpersons:

Miguel San Martin, NASA Jet Propulsion Laboratory

David Dannemiller, NASA Johnson Space Center

Local Chairpersons:

Jastesh Sud, Lockheed Martin Space Systems Company

Larry Germann, Left Hand Design Corp.

The following paper numbers were not assigned:

AAS 18-149 to -150

AAS 18-141

ADVANCED STATE ESTIMATION FOR ORION ORBITAL RENDEZVOUS: A Kalman-Batch Hybrid Filter for On-Orbit Bearing Estimation Using RF Information

William J. Pisano[*] and Philip G. Good[†]

Various Orion rendezvous and docking scenarios require relative positioning information to assure success. The traditional Radar mono-pulse approach used on the Space Shuttle requires additional hardware, and thus additional weight. As Orion is intended to be the next generation of spacecraft, capable of Lunar and Martian missions, launch weight comes at a premium and must be minimized. Modern in-flight computing capabilities enable sophisticated algorithms to be run in real-time, with the benefit that hardware functionality can be replicated with comparable, or even better results in software. Several algorithms capable of finding a relative bearing from received RF signal strength and antenna direction were studied, including Spiral Scanning, Gradient Descent, Recursive Least Squares, Linear Kalman Filter, Extended Kalman Filter, and Batch Filtering approaches. It was found that an approach using a combination of concepts from Extended Kalman filtering and Batch filtering, entitled Kalman Batch Hybrid (KBH) filtering, is able to locate a target and estimate it's bearing quickly and with minimal lag when compared to the other approaches. [View Full Paper]

[*] Ph.D., Infinite Horizon Co.
[†] Ph.D., Lockheed Martin Space Systems Company.

AAS 18-142

RE-EVALUATING ORION'S RELATIVE NAVIGATION FILTER DESIGN FOR NASA'S FUTURE EXPLORATION MISSIONS

David Woffinden,[*] Renato Zanetti,[†] Kirsten Tuggle,[‡] Christopher D'Souza[§] and Peter Spehar[**]

The vision of human exploration introduced by the Constellation Program over a decade ago demanded extensive capability from the Orion spacecraft. One of the critical flight elements included automated and piloted rendezvous and docking with multiple vehicles in Low Lunar Orbit (LLO) and Low Earth Orbit (LEO). To support the necessary rendezvous, proximity operations, and docking (RPOD) requirements, the design and development of the relative navigation system began. Following the cancellation of the Constellation Program and subsequent shifts in NASA's near term exploration goals, the need for the crewed Orion vehicle to perform RPOD was postponed along with the relative navigation filter development. Recently, NASA has begun procuring docking hardware to support upcoming exploration missions (EM) and the need to investigate Orion's rendezvous and docking capability has resurfaced. This paper revisits the relative navigation filter design and re-evaluates the selected formulation in context of past and current space programs, analyzes the performance and trades between different filter designs, and demonstrates the filter's performance in context of the proposed rendezvous and docking concept of operations (ConOps) envisioned for establishing a deep space gateway (DSG) in a lunar near rectilinear halo orbit (NRHO). [View Full Paper]

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AAS 18-143

RETRO-REFLECTOR PATTERN DESIGN AND IDENTIFICATION FOR ORION RENDEZVOUS, PROXIMITY OPERATIONS, AND DOCKING

Christopher Ertl,[*] John Christian[†] and Shane Robinson[‡]

Future Orion missions are expected to perform an Apollo-like transposition, docking, and extraction sequence after the trans-lunar injection (TLI) burn. During this sequence, Orion will observe the motion of the Exploration Upper Stage using a LIght Detection and Ranging (LIDAR) sensor. This process will be aided by observing a collection of retroreflectors mounted at known locations on the Exploration Upper Stage. In order to ensure robust retroreflector identification in the presence of spurious returns and without a-priori pose information, a holistic approach is taken to retroreflector pattern design and the development of reflector identification algorithms. Here several approaches to retroreflector placement, and identification are examined. [View Full Paper]

[*] Graduate Research Assistant, Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA.
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[‡] Aerospace Engineer, GNC Autonomous Flight Systems Branch, NASA Johnson Space Center, Houston, Texas 77058, USA.

AAS 18-144

RESTORE-L: ADVANCED IN-SPACE ROBOTIC SERVICING MISSION ENABLED BY A 3D FLASH LIDAR VISION NAVIGATION SENSOR (VNS) FOR HIGH PRECISION AUTONOMOUS RELATIVE NAVIGATION

Reuben R. Rohrschneider,* Stephen Lutgring† and James Masciarelli‡

On-Orbit Servicing capabilities are critical to our national interest. Such capabilities are: (a) necessary for maintaining world leadership in space for scientific, commercial, and strategic reasons, (b) required to manage, upgrade, service, inspect, and prolong the lifespans of costly, national orbiting assets, and (c) will enable the United States to expand the options for more resilient, efficient, and cost-effective operations in space. To address these issues, NASA is leading an ambitious, technology-rich Restore-L mission, an endeavor to launch a robotic spacecraft in 2020 to refuel a live satellite. The mission, the first of its kind in low-Earth orbit, will demonstrate that a suite of satellite-servicing technologies can perform in-space servicing of the client Landsat 7 satellite. To accomplish such an ambitious mission, an innovative autonomous relative navigation system is a key enabling technology. At Ball Aerospace, we have developed a cutting-edge 3D Lidar, named the Vision Navigation Sensor (VNS) and algorithms that enable high precision point cloud output for the Restore-L mission. In this paper, we present an overview of the Restore-L servicing mission with an emphasis on Ball Aerospace's 3D Lidar Vision Navigation Sensor VNS design, predicted performance, and test results which are vital for precision autonomous relative navigation. [View Full Paper]

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THE NATURAL FEATURE TRACKING AND LIDAR HYBRID APPROACH FOR OSIRIS-REX SAMPLE COLLECTION[*]

Ryan Olds,[†] Curtis Miller,[‡] Michael Skeen,[§] David Lorenz[**] and Kevin Berry[††]

The **O**rigins **S**pectral **I**nterpretation **R**esource **I**dentification and **S**ecurity-**R**egolith **Ex**plorer (OSIRIS-REx) mission utilizes an autonomous method for collecting a regolith sample from the surface of the asteroid Bennu. This sampling event is referred to as "TAG", or Touch and Go. A new design concept has been developed which utilizes a combination of autonomous optical navigation and rendezvous capabilities and is referred to as "Hybrid TAG". The primary sensors for executing Hybrid TAG include a Navigation Camera built by Malin Space Science Systems and a flash Lidar system built by Advanced Scientific Concepts. The baseline method for executing TAG utilizes only the Lidar sensor. A backup method was also later developed using optical navigation, referred to as Natural Feature Tracking (NFT). The recently developed Hybrid design combines the strengths of both these methods as it includes accurate asteroid-relative navigation using Natural Feature Tracking followed by high rate Lidar range measurements for approaching the sample collection site. This approach has the potential to improve TAG accuracy when compared to the Lidar-only method and also potentially allows a wider range of possible TAG sites to be accessible. These advantages are contingent on the environment encountered at Bennu and depending on what is discovered as the mission explores Bennu, the most appropriate TAG method will be chosen to collect the sample. This new Hybrid TAG method reduces risk and improves the robustness of the OSIRIS-REx primary science objective. [View Full Paper]

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AAS 18-146

ON A GENERAL FORMULATION OF RELATIVE MOTION AND BURN TARGETING FOR NON-CIRCULAR RENDEZVOUS

Matthew C. Wilkinson[*] and David P. Dannemiller[†]

Relative motion and burn targeting in the case of circular rendezvous, i.e. where the orbit of the target vehicle has negligible eccentricity, is fairly straightforward and understood. Relative motion in the Local Vertical Curvilinear frame is well approximated by the Clohessy-Wiltshire set of linear equations. Once the orbit of the target vehicle becomes elliptical this formulation no longer accurately describes motion of the chaser vehicle, and the motion between the vehicles differs based upon the respective times since periapsis of the two vehicles. In this paper the authors present a generalized formulation of relative motion and targeting that extends to any target orbit eccentricity, while maintaining identically the Clohessy-Wiltshire state transition matrix. [View Full Paper]

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AAS 18-147

SAMPLING-BASED RECEDING HORIZON GUIDANCE FOR THE SAFE INSPECTION OF A TUMBLING SPACECRAFT

Francesco Capolupo* and Stijn Mast†

Over the past few years, the complexity of upcoming rendezvous, active debris removal and servicing missions has constantly increased, requiring new and innovative Guidance Navigation & Control techniques to achieve ambitious missions' goals. Among all the proposed mission scenarios, the inspection of a non-cooperative, tumbling target vehicle by a chaser spacecraft is a very challenging one that requires to take into account many constraints, among which the rotational state of the target, the illumination conditions, the chaser's attitude and position control limitations, as well as collision avoidance constraints. This paper presents a Sampling Based Predictive Guidance algorithm that allows inspecting a tumbling target, while ensuring an arbitrary low risk of collision between the two spacecraft. The core of the algorithm consists in numerically exploring the admissible command space obtained by assigning to each admissible maneuver a score, which is function of the inspection properties of the trajectory that follows the maneuver. A simple heuristic is used to bias the exploration towards the most interesting regions of the command space, in order to identify and execute the globally optimal maneuver within the space. A new and computationally simple method to guarantee the safety of the two vehicles is also presented, and implemented into the algorithm. The proposed method allows taking into account relative navigation and maneuver execution errors when planning safe inspection trajectories. The results obtained by our algorithm are compared to the ones obtained with a classic inspection strategy using inclined football orbits. It is shown that the proposed guidance algorithm robustly and safely ensures the completion of the inspection mission, and exploits the characteristics of the natural dynamics of the system to outperform the classical approach. To conclude, the advantages of using Sampling-Based Motion Planning techniques to compute trajectories for complex proximity operations are highlighted and discussed.

[View Full Paper]

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AAS 18-148

OPTIMAL MANEUVERS FOR SAFE RPO USING RELATIVE ORBITAL ELEMENTS AND SEQUENTIAL CONVEX PROGRAMMING

Nicholas G. Ortolano,* David K. Geller† and Aaron Avery‡

Passive safety of flight constraints for orbital rendezvous and proximity operations trajectory design are imposed as a means for ensuring zero probability of collision in the event of a passive failure on the chaser satellite. For a chaser satellite near a target satellite in a near circular reference orbit, relative orbital elements are used to develop safety of flight constraints. Using relative orbital elements, the problem is formulated as a minimum Δv convex optimization problem in which the optimal transfer trajectories are guaranteed to not pass within a prescribed distance of the target satellite in the event of a passive failure such as power loss, computer shutdown/reboot, or a suspension of normal activities due to mission/vehicle anomalies. The nonconvex constraints are convexified via linearized approximations and implemented in a sequential convex optimization problem.

[View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE, NAVIGATION AND CONTROL

Session 16

National Chairpersons:

Bill Frazier, NASA Jet Propulsion Laboratory

Neil Dennehy, NASA Goddard Space Flight Center

Local Chairpersons:

Alex May, Lockheed Martin Space Systems Company

Brian Kirby, University of Colorado/LASP

The following papers were not available for publication:

AAS 18-157 (Paper Withdrawn)

AAS 18-158 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 18-159 to -160

AAS 18-151

FLYING CASSINI THROUGH THE GRAND FINALE ORBITS: PREDICTION VS. REALITY

Mar Vaquero,* Yungsun Hahn, Sonia Hernandez, Frank Laipert, Powtawche Valerino, Sean Wagner, Mau Wong and Duane Roth†

After twenty years of successful mission operations and invaluable scientific discoveries, the Cassini orbiter completed its tour around the Saturnian system on the most complex gravity-assist trajectory ever flown. The end-of-mission target of September 15, 2017 was achieved by preserving propellant at the expense of minimizing maneuver cycles. A navigation strategy that incorporated orbit trim maneuvers was developed five years in advance to maintain position dispersions below 250 km (1σ) at three specific periapses, following the last targeted flyby in the mission. This paper reports on the actual maneuver performance and overall trajectory control to maintain the Grand Finale orbits, highlighting the differences between predicted and implemented values. [View Full Paper]

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AAS 18-152

CASSINI ORBIT DETERMINATION OPERATIONS THROUGH THE FINAL TITAN FLYBYS AND THE MISSION GRAND FINALE (FEBRUARY 2016 – SEPTEMBER 2017)

Julie Bellerose,[*] Duane Roth,[†] Dylan Boone,[‡] Zahi Tarzi,[‡] Rodica Ionasescu[‡] and Kevin Criddle[‡]

This paper reports on the orbit determination performance for the final 1.5 years of the Cassini Solstice mission, including the mission's Grand Finale. During this period, Cassini encountered its final eleven targeted flybys of Titan (T116-T126) and executed its last 62 orbits of Saturn. In these final months, the spacecraft's inclination was gradually raised from near equatorial to near 63 degrees, critical inclination, to prevent the line of apsides from rotating out of Titan's orbital plane. Critical inclination enables continued Titan flybys, the last of which places Cassini on an impact trajectory with Saturn, thereby satisfying planetary protection requirements. In this reporting period, the orbit period moved from 16 days to nearly 32 and, for the final 6 months, it was brought down to less than 7 days. By design, the spacecraft entered the Saturn atmosphere on its final orbit and vaporized on September 15, 2017. We also report on the particular challenges associated with a stellar occultation, a flyby of Saturn's rocks, and the last revolutions of the mission's Grand Finale.

[View Full Paper]

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AAS 18-153

THE UNEXPECTED ROOT CAUSE CONCLUSIONS OF REACTION WHEEL FAILURES ON KEPLER AND FUSE

Bill Bialke* and Eric Hansell†

After a series of unresolved bearing failures and friction anomalies on spacecraft utilizing ITHACO reaction wheels, a Relentless Root Cause Analysis completed by United Technologies Corporation led to unexpected conclusions which implicated the space charging environment as a likely root cause, and which had not been considered in many previous failure investigations. A strong correlation of the space-charging environment with a statistically significant number of friction events observed on-orbit was supported by the results of laboratory tests, which successfully duplicated the friction event signatures. Countermeasures were developed to minimize the occurrence of friction events and to increase the probability of successful recovery from anomalous friction increases. This phenomenology likely has applications beyond reaction wheels and should be considered for all past and future mechanisms using ball bearings. [View Full Paper]

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AAS 18-154

ESA'S RECENT EXPERIENCE WITH REACTION WHEEL PERFORMANCE

René Seiler,* Florian Liebold,* Tobias Haefner* and Daniel Bojiloff*

Reaction wheel performance is a crucial aspect for the design and fidelity of spacecraft attitude control systems. Over the past years, the European Space Agency in cooperation with industrial partners has conducted a number of investigations to characterize, for instance, the evolution of the friction torque or 'mi-crovibration signatures' for European reaction wheel products as typically used on ESA spacecraft. These investigations included analysis of in-flight telemetry data, dedicated on-ground testing as well as computer-based modelling & simulation. Thereby, it has been possible to gain knowledge about equipment behaviour during crucial mission phases as well as various operational scenarios. In this context, also performance anomalies such as elevated friction torque and erratic torque fluctuations have been analysed, and their physical causes investigated. This has resulted in high-fidelity performance models, which may be used, among others, by the designers of new spacecraft attitude control systems. [View Full Paper]

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SEXTANT X-RAY PULSAR NAVIGATION DEMONSTRATION: INITIAL ON-ORBIT RESULTS[*,†]

Jason W. Mitchell, Luke B. Winternitz, Munther A. Hassouneh, Samuel R. Price, Sean R. Semper, Wayne H. Yu,[‡] Paul S. Ray, Michael T. Wolff, Matthew Kerr,[§] Kent S. Wood,[**] Zaven Arzoumanian, Keith C. Gendreau,[‡] Lucas Guillemot, Ismaël Cognard[††] and Paul Demorest[‡‡]

The Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) is a technology demonstration enhancement to the Neutron-star Interior Composition Explorer (NICER) mission. SEXTANT will be a first demonstration of in-space, autonomous, X-ray pulsar navigation (XNAV). Navigating using millisecond X-ray pulsars which could provide a GPS-like navigation capability available throughout our Solar System and beyond. NICER is a NASA Astrophysics Explorer Mission of Opportunity to the International Space Station that was launched and installed in June of 2017. During NICER's nominal 18-month base mission, SEXTANT will perform a number of experiments to demonstrate XNAV and advance the technology on a number of fronts.

In this work, we review the SEXTANT, its goals, and present early results from SEXTANT experiments conducted in the first six months of operation. With these results, SEXTANT has made significant progress toward meeting its primary and secondary mission goals. We also describe the SEXTANT flight operations, calibration activities, and initial results. [View Full Paper]

[†] This work is funded by NASA Space Technology Mission Directorate, Game Changing Development Program.

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AAS 18-156

SUCCESSFUL VENUS ORBIT INSERTION OF AKATSUKI USING ATTITUDE CONTROL THRUSTERS

Chikako Hirose,[*] Nobuaki Ishii,[†] Masatoshi Ebara,[‡] Takeshi Oshima,[‡] Kota Matsushima,[‡] Tomoya Fujita,[§] Hiroshi Terada,[‡] Chiaki Ukai,[‡] Junichi Nakatsuka,[†] Keisuke Michigami,[†] Katsumi Furukawa,[**] Daijiro Shiraiwa,[**] Kozo Otani,[‡] Sumito Shimomura[††] and Masato Nakamura[†]

The Venus explorer "Akatsuki" made an attempt of Venus orbit insertion in 2010, which failed due to malfunctions of the orbit maneuvering engine. In 2015, a second attempt was made that successfully inserted into orbit about Venus. Although unintended, it became the world's successful orbit insertion using attitude control thrusters. This paper reports what is required for orbital maneuver operation by a reaction control system and how the autonomous controls of spacecraft are con-figured for the successful orbit insertion in detail.

[View Full Paper]

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[††] NEC Networks & System Integration Corporation, 2-6-1 Koraku, Bunkyo-ku, Tokyo 112-8560 Japan.

POSTER SESSION

Poster Session

Local Chairperson:

Reuben Rohrschneider, Ball Aerospace & Technologies Corp.

The following papers were not available for publication:

Entry, Descent, and Landing Guidance with Direct Force Control Using Aerodynamic Shape Morphing, R. Lugo, R. Powell (AMA), A. Slagle, A. Korzun, A. Cianciolo (NASA) (Poster Only)

Vision based tracking controller for an on-orbit meteor observer, R. T. Nallapu, A. Ravindran, J. Thangavelautham (University of Arizona) (Poster Only)

Spacecraft Attitude Control Using Circulating Liquid Metals, J. Thangavelautham, R. T. Nallapu (University of Arizona) (Poster Only)

Reaction Wheel Energy Storage in a Small Satellite M. Duntz, F. Fogle, L. Sauter (United States Air Force Academy) (Poster Only)

On-Orbit Satellite Servicing Using Multiple Tethered Robots, H. Kalita (University of Arizona) (Poster Only)

Dither Gyro Scale Factor Calibration the GOES-16 Flight Experience, A. Reth (Chesapeake Aerospace) (Poster Only)

AAS 18-161

IMPULSIVE THRUSTER BASED ATTITUDE STABILITY ANALYSIS OF SPACECRAFT WITH FLEXIBLE SOLAR ARRAYS

Cody Allard,[*] Scott Piggott[†] and Hanspeter Schaub[‡]

Stability analysis is an important tool in determining the robustness of the control system design for spacecraft missions. However, many spacecraft exhibit flexible dynamics due to solar arrays or other appended bodies. Therefore, the stability analysis needs to incorporate flexing behavior in the equations of motion. This paper outlines a method for analyzing the stability of spacecraft with flexing solar arrays using classical linear stability analysis techniques such as Bode plots and gain and phase margins. In order to use classical methods for stability analysis, the nonlinear equations that describe the dynamics of spacecraft with flexing solar arrays first need to be linearized. Another aspect to this problem is the equations of motion for the flexing and spacecraft rotation are coupled through second order state variables. This requires the system mass matrix to be inverted to fit the classical state space form. Finally, an eigenvalue diagonalization on the dynamics matrix is necessary to analyze the transfer functions for the stability analysis tools to show the impact of flexing on the performance. This paper summarizes the methods used for the stability analysis and compares the analytical results to numerical results found by simulating a flexible spacecraft using the Basilisk astrodynamics software package. Additionally, the results are compared to rigid body stability analysis results which shows the key influence of flexing on the robustness of the control design. [View Full Paper]

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[†] ADCS Integrated Simulation Software Lead, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder.
[‡] Professor, Glenn L. Murphy Chair, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, USA. AAS Fellow.

A MICRO NEWTON IMPULSE-BIT HYDRAZINE THRUSTER—DESIGN, TEST, AND MISSION APPLICATIONS*

J. Morgan Parker,† John Blandino,‡ David Skulsky,§
James R. Lewis** and Daniel P. Scharf††

A small thruster, that will herein be called the Hydrazine milliNewton Thruster (HmNT), has been designed and vacuum hot-fire tested, demonstrating a range of thrust and impulse far below the current state-of-the-art (SOA) hydrazine thruster. Steady-state thrust levels of 35–135 mN, and minimum impulse-bits of 25–120 µN-s were demonstrated over a typical operating range of inlet pressures. These capabilities provide new spacecraft and mission design options, including the following.

- Functional backup for Reaction Wheel Assemblies (RWAs), which can be used to prolong the useful life of RWAs
- RWA replacement for certain missions to save mass, power, and cost
- Precision delta-V that can be used for
  - proximity operations and docking maneuvers
  - formation flying
  - primary attitude control for SmallSats and CubeSats
  - primary delta-V for CubeSats. [View Full Paper]

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NUMERICAL INDEX*

VOLUME 164 I & II ADVANCES IN THE ASTRONAUTICAL SCIENCES, GUIDANCE, NAVIGATION AND CONTROL 2018 (2018)

(41st AAS Rocky Mountain Guidance and Control Conference, February 1–7, 2018, Breckenridge, Colorado, U.S.A.)

* Unless otherwise indicated all papers appear in Volume 164, *Advances in the Astronautical Sciences*.

AAS 18-037 Continuous Electrode Inertial Electrostatic Confinement Fusion, R. J. Sedwick, A. M. Chap and N. M. Schilling (Part I)

AAS 18-038 to -040 Not Assigned

AAS 18-041 GNC Implementations for Small Interplanetary and Lunar Spacecraft, Matthew Baumgart, Michael Ferenc, Daniel Hegel, Bryan Rogler and Devon Sanders (Part I)

AAS 18-042 Mobility and Science Operations on an Asteroid Using a Hopping Small Spacecraft on Stilts, Himangshu Kalita, Stephen Schwartz, Erik Asphaug and Jekan Thangavelautham (Part I)

AAS 18-043 Dynamic Programming Based Attitude Trajectories for Underactuated Control Systems, Vedant and Alexander Ghosh (Part I)

AAS 18-044 Sensor Fusion for Attitude Determination, Vedant, Yukti Kathuria and Alexander Ghosh (Part I)

AAS 18-045 Advanced GNC Techniques for Autonomous Rendezvous Proximity Operations and Docking of Small Satellites, Christopher W. T. Roscoe, Jason J. Westphal, Jason R. Crane and Islam I. Hussein (Part I)

AAS 18-046 Not Available (Withdrawn)

AAS 18-047 Verification of Attitude Determination and Control Capabilities for CubeSat-Class Spacecraft, Matt Sorgenfrei, Jordan Liss and Dayne Kemp (Part I)

AAS 18-048 Generalization of the Effects of Atmospheric Density Uncertainties on the Probability of Collision, Charles D. Bussy-Virat, Aaron J. Ridley and Joel W. Getchius (Part I)

AAS 18-049 to -050 Not Assigned

AAS 18-051 COBALT: Terrestrial Flight Test of Landing Navigation Using Lander Vision System with Navigation Doppler Lidar, Steven M. Collins, Carl R. Seubert, Ara Kourchians, Carlos Y. Villalpando and John M. Carson III (Part I)

AAS 18-052 Aerocapture System Options for Delivery of Small Satellites to Mars, G. Falcone, J. W. Williams and Z. R. Putnam (Part I)

AAS 18-053 Entry, Descent, and Landing Performance for a Mid-Lift-to-Drag Ratio Vehicle at Mars, Breanna J. Johnson, Ellen M. Braden, Ronald R. Sostaric, Christopher J. Cerimele and Ping Lu (Part I)

AAS 18-054 Fuel-Optimal and Apollo Powered Descent Guidance Compared for High-Mass Mars Mission, Ping Lu (Part I)

AAS 18-055 Not Available (Withdrawn)

AAS 18-056 to -060 Not Assigned

AAS 18-061 Dynamics and Control of a Tethered Enhanced Gravity Tractor Performing Asteroid Deflection, Haijun Shen, Carlos M. Roithmayr and Yingyong Li (Part I)

AAS 18-062 OSIRIS-REx Navigation Performance During First Leg of Outbound Cruise, Peter G. Antreasian, Jason M. Leonard, Jim V. McAdams, Michael C. Moreau, Brian Page, Daniel R. Wibben and Kenneth E. Williams (Part I)

[*] Most of the Poster Session presentations did not consist of formal written text, and therefore most of the material presented in this session was not available for publication.

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