GUIDANCE, NAVIGATION, AND CONTROL 2014

Edited by
Alexander J. May

American Astronautical Society

Volume 151

ADVANCES IN THE ASTRONAUTICAL SCIENCES

GUIDANCE, NAVIGATION, AND CONTROL 2014

EDITOR
Alexander J. May — Lockheed Martin Space Systems Co.

SERIES EDITOR
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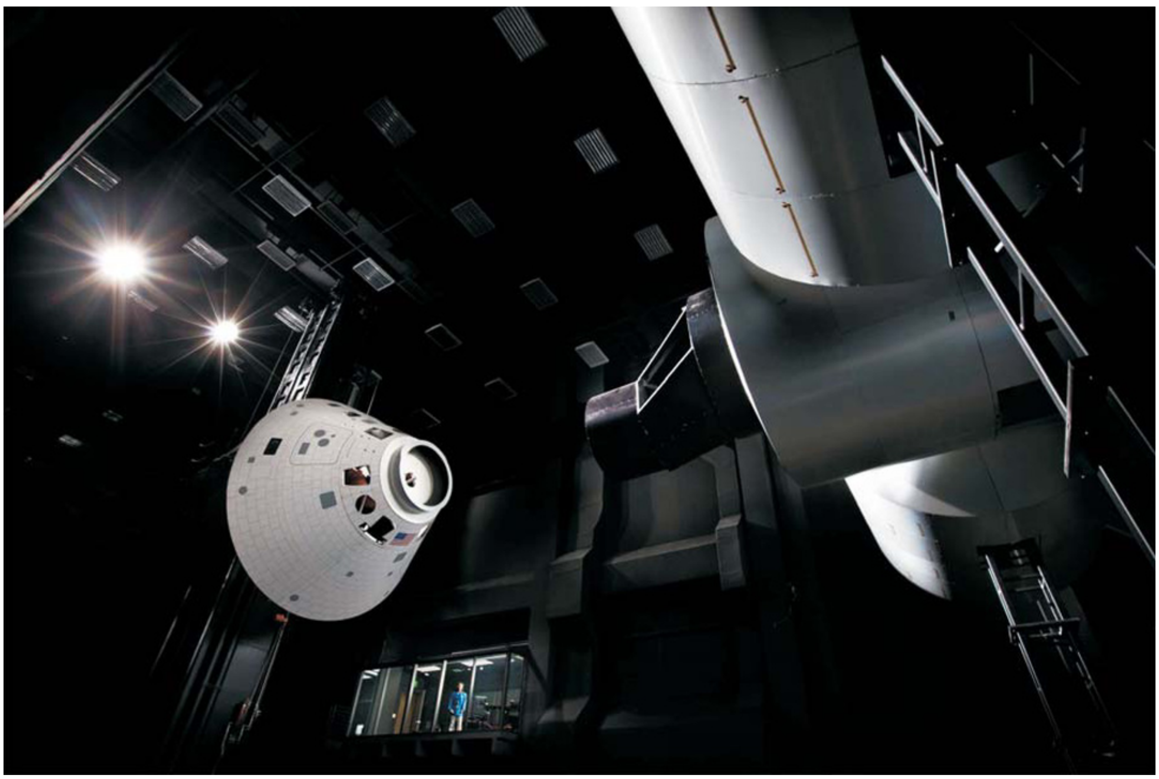
Front Cover Illustration:

Lockheed Martin is the prime contractor building the Orion multi-purpose crew vehicle, NASA's first spacecraft designed for long-duration, human-rated deep space exploration. Orion will transport humans to interplanetary destinations beyond low Earth orbit, such as asteroids, the moon and eventually Mars, and return them safely back to Earth. Credit: Lockheed Martin.

Frontispiece:

Lockheed Martin's state-of-the-art Space Operations Simulation Center (SOSC) has completed orbital simulation tests with hardware and data that was flown on NASA's STS-134 space shuttle *Endeavour* mission to the International Space Station. The tests have demonstrated the center's ability to replicate on-orbit conditions that affect relative navigation, lighting and motion control in space — providing a simulated space dynamics and lighting environment that is unparalleled in the space industry. Credit: Lockheed Martin.



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FOREWORD

HISTORICAL SUMMARY

The annual American Astronautical Society Rocky Mountain Guidance 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, collaborating on a guidance and control project, met in the Colorado Rockies for a working ski week. They jointly came up with the idea of convening a broad spectrum of experts in the field for a fertile exchange of aerospace control ideas, and a concurrent ski vacation. At about this same time, Dan DeBra and Lou Herman discussed a similar plan while on vacation skiing at Keystone.

Back in Denver, 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 the last 19 years. The 2014 Conference was the 37th Annual AAS Rocky Mountain Guidance 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, and was adhered to strictly until 2013. No parallel sessions, three-hour technical/tutorial sessions at daybreak and late afternoon, and a six-hour ski break at midday are the biblical constraints. 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 that more than justified the hard play between sessions.

After the 2012 conference, it was clear that overall industry budget cuts and a mis-conception by industry and government leaders that this conference was a ski trip with a few side conversations were leading to reduced attendance and support. In an effort to meet the needs of the constituents, several changes were suggested that did not meet the original founding style. The first implementation of these changes was to add parallel sessions for 3 of the 8 sessions on a trial basis during the 2013 conference. The success of the parallel sessions was carried forward to 2014 and is expected to continue indefinitely.

A tradition from the beginning and retained until 2014 had been the Conference banquet. It was an elegant feast marked by informality and good cheer. 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 Observations: Challenges and Responsibilities."

2011 Joe Tanner, Former NASA Astronaut, Senior Instructor, University of Colorado, "Building Large Structures in Space."

2012 Greg Chamitoff, 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.

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

OBSERVATIONS: CHALLENGES AND RESPONSIBILITIES

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."

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 a $70,000 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

Academic Year	Aerospace Engr Sciences	Electrical and Computer Engr
1981–1982	Jim Chapel	
1982–1983	Eric Seale	
1983–1984	Doug Stoner	John Mallon
1984–1985	Mike Baldwin	Paul Dassow
1985–1886	Bruce Haines	Steve Piche
1986–1987	Beth Swickard	Mike Clark
1987–1988	Tony Cetuk	Fred Ziel
1988–1989	Mike Mundt	Brian Olson
1989–1990	Keith Wilkins	Jon Lutz
1990–1991	Robert Taylor	Greg Reinacker
1991–1992	Jeff Goss	Mark Ortega
1992–1993	Mike Goodner	Dan Smathers
1993–1994	Mark Baski	George Letey
1994–1995	Chris Jensen	Curt Musfeldt
1995–1996	Mike Jones	Curt Musfeldt
1996–1997	David Son	Kirk Hermann
1997–1998	Tim Rood	Ui Han
1998–1999	Erica Lieb	Kris Reed
1999–2000	Trent Yang	Adam Greengard
2000–2001	Josh Wells	Catherine Allen
2001–2002	Justin Mages	Ryan Avery
2002–2003	Tara Klima	Kiran Murthy
2003–2004	Stephen Russell	Andrew White
2004–2005	Trannon Mosher	Negar Ehsan
2005–2006	Matthew Edwards	Henry Romero
2006–2007	Arseny Dolgov	Henry Romero
2007–2008	Christopher Aiken	Kirk Nichols
2008–2009	Nicholas Hoffmann	Gregory Stahl
2009–2010	Filip Maksimovic	Justin Clark
2010–2011	John Jakes	Filip Maksimovic
2011–2012	Wenceslao Shaw-Cortez	Andrew Thomas
2012–2013	Jacob Haynes	Nicholas Mati
2013–2014	Kirstyn Johnson	Caitlyn Cooke

In 2013, in an effort to obtain more 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 address hardware and software research as well as component, system, or simulation advances. Papers submitted must have a student as the primary author and presenter. 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. The SpaceX Grand Prize Award for Excellence in the field of GN&C by a Student was awarded.

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"

The Rocky Mountain Section of the American Astronautical Society established a broad-based Conference Committee, the Rocky Mountain Guidance and Control Committee, chaired ex-officio by the next Conference Chair, to run the annual Conference. The Conference has been a success from the start. The Conference, now named the AAS Guidance, Navigation and Control Conference, and sponsored by the national AAS, attracts about 200 of the nation's top specialists in space guidance 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	140
2013	Lisa Hardaway	181
2014	Alexander May	180

The AAS Guidance 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 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 and control experts for years to come.

On behalf of the Conference Committee and the Section,

Alexander J. May
Lockheed Martin Space Systems Company
Littleton, Colorado

PREFACE

This year marked the 37th anniversary of the AAS Rocky Mountain Section's Guidance and Control Conference. It was held in Breckenridge, Colorado at the Beaver Run Resort from January 31 – February 5, 2014. 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 Friday morning with a pair of new, classified sessions hosted at Lockheed Martin's facility in the Denver Metro area. 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*. As one would expect, these presentations are not publishable.

The traditional five day conference format officially began on Saturday morning with a follow up to last year's very impressive *Student Innovations in GN&C* session featuring a student competition with scholarship prizes.

To cap off the day, the *Technical Exhibits* session was held Saturday afternoon. Twenty companies and organizations participated with many hardware demonstrations as well as excellent technical interchanges between conferees, vendors, and family. The session was accompanied by a buffet dinner. Many family members and children were present, greatly enhancing the collegiality of the session. The highly-experienced technical exhibits team did an outstanding job organizing the vendors and exhibits.

Other sessions during the conference examined the current state-of-the-art and the future of GN&C. Two sessions, *Advances in GN&C in Hardware* and *Advances in GN&C in Software*, were run concurrently on Sunday morning. A session on *HWIL Testbeds and Demonstration Laboratories* which are critical to verify performance in a test-like-you-fly environment occurred on Tuesday afternoon. *Adaptive & Optimal Control* presented where appreciable GN&C performance improvements have been attained in dynamic systems. Also included was a special session dedicated to *ORION Multi-Purpose Crew Vehicle GN&C,* highlighting launch abort capabilities and navigation systems to future exploration mission concepts and design references.

Another key focus this year related to our economic times. *CubeSats & SmallSats* are gaining in popularity and utility at a fraction of the cost with capabilities rivaling traditional larger satellites for some missions, and this session showed how that is happening. *Hosted Payloads* showed they can offer enhanced affordability, but unique challenges and considerations must be addressed as presented in this session. *Saving the Spacecraft: Rescues, Fault Protection, & Life Extensions* shared both historic and modern stories of not letting our precious assets fail. Similarly, *Mixed Actuator Attitude Control* discussed specific solutions to keeping vehicles controlled when an actuator goes out.

Continuing in the educational spirit, Analytical Graphics, Inc. held a special workshop to teach about *Spacecraft Simulations in STK*. We were fortunate to have astronaut Joe Tanner give an exciting presentation to the children visiting with us at the conference. And also, we had a daily *Poster Session* where posters were on display so attendees could speak one-on-one with the authors during breakfast and break periods.

The traditional banquet on Monday evening was revamped to offer better networking opportunities. We were very pleased to have our keynote speakers for the evening, Neil Dennehy, NASA's Technical Fellow for GN&C, and Stephen Airey from the European Space Agency, give great insights to "Issues Concerning the GN&C Community."

Finally, Wednesday morning featured the popular closing session *Recent Experiences*. This traditional session contained candid first-hand accounts of the successes and failures, trials and tribulations encountered in the space industry with valuable lessons for all to help ensure continued successes in the future.

The participation and support of our many colleagues in the industry helped make the 37th Annual Rocky Mountain AAS G&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 goes to Carolyn O'Brien 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!

Alexander J. May, Conference Chairperson
2014 AAS Guidance and Control Conference

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STUDENT INNOVATIONS IN GUIDANCE, NAVIGATION AND CONTROL

SESSION I

This session embraced the wealth of research and innovative projects related to spacecraft GN&C being accomplished in the university setting. Papers in this session addressed hardware/software research as well as component, system or simulation advances. Papers submitted were required to have a student as the primary author and presenter. Papers were adjudicated based on level of innovation, complexity of problem solved, perceived technical readiness level, applicability and fieldability to near-term systems, clarity of written and verbal delivery, number of completed years of schooling and adherence to delivery schedule. Prizes were awarded to the top 3 papers sponsored by: Space X, Sierra Nevada Corp. and Intuitive Machines, LLC.

National Chairperson:	Tim Crain Intuitive Machines
Local Chairpersons:	Dave Chart Lockheed Martin Space Systems Company
	Ian Gravseth Ball Aerospace & Technologies Corp

The following papers were not available for publication:

AAS 14-011
(Paper Withdrawn)

AAS 14-012
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 14-019 to -020

GENERAL-USE SIMULINK HARDWARE AND ENVIRONMENT MODELS AND APPLICATIONS IN CONTROL SIMULATION AND ANALYSIS

Nicholas Ravago*

This paper outlines some of the work done as an undergraduate intern over two summer sessions during 2012 and 2013 at NASA Goddard Space Flight Center. Hardware modeling can consume an unnecessary amount of time and effort if engineers are independently constructing their own models for similar purposes. To save future mission analysts time, models of past satellites were examined to create general-use SIMULINK models for components such as magnetic torquer bars and three-axis magnetometers as well as environmental forces. To demonstrate their use, a full attitude control system simulation was created using these models to analyze how to most effectively unload spacecraft momentum using magnetic torquer bars. The simulation utilized an optimization constant method to unload momentum efficiently without disturbing spacecraft attitude. [View Full Paper]

* First-Year Graduate Student, Colorado Center for Astrodynamics (CCAR), ECNT 320, 431 UCB, University of Colorado at Boulder, Colorado 80309-0431, U.S.A.

AAS 14-014

DENSITY MODEL CORRECTIONS AT LOW ALTITUDES DERIVED FROM ANDE ORBIT DATA

Travis Lechtenberg[*] and Craig A. McLaughlin[†]

This paper examines atmospheric densities derived from ANDE (Atmospheric Neutral Density Experiment) orbit data during the course of the satellite lifetimes. These satellites' missions occurred while the Sun was relatively quiet, with the second ANDE mission occurring during solar minimum. This results in less variability in the atmosphere, and is expected to allow better observation of thermospheric density structures. The results are compared to density values given by both Jacchia and NRLMSISE-00 atmospheric density models. The deviation from the model densities will be compared to model deviations for the CHAMP and GRACE satellites which also have independent atmospheric density calculations via the high accuracy accelerometers carried by the satellites. Better understanding of atmospheric density variations will allow orbits to be more accurately predicted and is a key component to delaying or even preventing the Kessler syndrome. [View Full Paper]

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VISION-BASED RELATIVE NAVIGATION FILTER FOR ASTEROID RENDEZVOUS

Dylan Conway, Brent Macomber, Kurt A. Cavalieri[*] and John L. Junkins[†]

This paper presents a novel navigation strategy for spacecraft small-body proximity operations. The method uses co-registered color and depth images to map the surface of a body while simultaneously localizing the spacecraft relative to the generated map. Motion parameters of the body are estimated in the filter and used in state propagation. The method is implemented in a laboratory experiment and can run at the 30 Hz frame rate of the sensor. The filter results are compared to ground-truth data for validation. [View Full Paper]

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AAS 14-016

CLOSED-LOOP GN&C LINEAR COVARIANCE ANALYSIS FOR MISSION SAFETY

Alex C. Perez[*]

A novel mission safety software program is developed to determine the trajectory dispersions of a chaser vehicle along a rendezvous or inspection trajectory using a closed-loop linear covariance technique. Given simulation parameters, system uncertainties, and a nominal trajectory, the program will quickly calculate the trajectory dispersions, navigation errors and the required maneuver Δv for the given trajectory. The non-linear dynamics of a six degree-of-freedom Monte Carlo simulation are linearized and linear covariance analysis is implemented to determine 3-σ trajectory dispersions and navigation errors. This information can be used to quantify the probability of collision and thus determine a bench-mark for mission safety along the chosen, nominal trajectory. These features are illustrated with a simple satellite inspection example.
[View Full Paper]

* Graduate Research Assistant, Mechanical and Aerospace Engineering Department, Utah State University, 4130 Old Main Hill, Logan, Utah 84322, U.S.A.

AAS 14-017

A NEW SOLUTION FOR THE GENERALIZED LAMBERT'S PROBLEM

Robyn M. Woollands,[*] John L. Junkins[†] and Ahmad Bani Younes[‡]

A method is presented for solving boundary and initial value problems in celestial mechanics. In particular we consider the well-known Lambert TPBVP. The approach is quite general, however certain details in the transformed space boundary conditions pose challenges. We have been able to resolve these difficulties fully for the planar classical two-body problem, and we are engaged in a study to extend our numerical algorithm to the generally perturbed case. This method fuses three sets of ideas: (i) Picard Iteration, (ii) Orthogonal approximation, and notably, regularizing transformation of the equations of motion. Curiously, we find that a local-linearization-based shooting is not required, and we also illustrate that the method is not highly sensitive to the starting approximation. Two variants of the approach are considered, with the first model utilizing a Picard Iteration operating on the general differential equations in rectangular coordinates, which are approximated by Chebyshev polynomials. The second variant makes use of the KS transformation to render the unperturbed motion rigorously linear. These techniques combined improve the time interval over which the Picard Iteration converges, and increases the speed of convergence over all time intervals. A numerical study demonstrates excellent execution time efficiency, and shows that these algorithms are also attractive for parallelization if needed for further computational speedup. These new algorithms address improvements in the solutions of a fundamental problem in astrodynamics and should find widespread use in contemporary and future applications.
[View Full Paper]

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‡ Assistant Professor, Department of Aerospace Engineering, Khalifa University, Abu Dhabi, UAE 127788.

AAS 14-018

MISSION CONSIDERATIONS FOR DIRECT TRANSFERS TO A DISTANT RETROGRADE ORBIT

Chelsea M. Welch* and Jeffrey S. Parker†

This paper discusses the applications of Distant Retrograde Orbits (DROs) about the Moon in support of advanced concepts such as NASA's Asteroid Redirect Mission. It studies how to build a direct transfer from a low Earth orbit to a DRO, paying attention to the guidance, navigation, and control challenges of each transfer option. The characteristics of planar DROs in the Earth-Moon system are examined. The paper focuses on a DRO that is in a 2:1 resonance with the lunar synodic period. Trade studies illustrate the relationships between the transfer trajectory duration, required launch energy, and DRO orbit insertion Δv cost. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL SOFTWARE

SESSION III

The GN&C hardware is often dependent on or successful due to GN&C software. This session is open to all GN&C software ranging from on orbit software used to drive or process data, ground software used for operations or simulation software used to test, validate or develop GN&C systems. This session highlights GN&C software from all aspects. **Note**: Advances in hardware applications are covered in *Session IV, Advances in Guidance, Navigation and Control Hardware*.

National Chairpersons:

Stephen "Phil" Airey
ESA TEC-ECC

Tooraj Kia
NASA / JPL

John Wirzburger
Johns Hopkins University
Applied Physics Laboratory

Local Chairpersons:

Lee Barker
Lockheed Martin
Space Systems Company

Jim Chapel
Lockheed Martin
Space Systems Company

The following paper was not available for publication:

AAS 14-036
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 14-031 and -039 to -040

DISTRIBUTED GN&C FLIGHT SOFTWARE SIMULATION FOR SPACECRAFT CLUSTER FLIGHT*

Shaun M. Stewart,† Lucas Ward‡ and Stacey Strand§

A spacecraft simulation environment was developed for testing distributed spacecraft flight software (FSW) designed for autonomous coordinated control of a spacecraft cluster. The Cluster Flight Application (CFA) FSW was developed by Emergent Space Technologies in support of the Defense Advanced Research Projects Agency (DARPA) System F6 Program. The CFA provides cluster flight guidance, navigation, and control (GN&C) functionality for controlling a cluster of spacecraft. This paper provides an overview of the Distributed Integrated Environment for CFA Analysis, Simulation, and Testing (DIECAST) used for CFA FSW development, verification and validation testing, and evaluation of CFA performance, reliability, and robustness. [View Full Paper]

* Distribution Statement "A" (Approved for Public Release, Distribution Unlimited).

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IONOSPHERIC DELAY MODELING FOR SINGLE FREQUENCY GPS SPACE USERS*

Lee Barker† and Chuck Frey‡

On May 7, 2011, Lockheed Martin successfully launched the first of a new series of Space-Based Infrared System (SBIRS) satellites, SBIRS GEO1. SBIRS is intended primarily to provide enhanced strategic and theater ballistic missile warning capabilities. SBIRS GEO1 design includes a dual frequency GPS receiver to support spacecraft navigation requirements. Early orbit checkout of GEO1 provided a unique look at the GPS environment at geosynchronous altitude, an opportunity to study phenomena like ionospheric delay and L1 antenna group delay from beyond the terrestrial and low Earth orbit regime (LEO), and develop improved GPS signal models to address this more challenging signal environment.

Many DOD and government users, such as NASA, are proposing using GPS signals at GEO as their primary method of orbit estimation. User navigation accuracy and robustness requirements have spurred interest in developing GPS navigation systems designed to operate in the space environment beyond LEO environment. Single frequency users in LEO may also benefit from improved signal modeling. Understanding the complete signal environment remains key to designing successful systems.

In the author's earlier paper, "GPS at GEO: A First Look at GPS from SBIRS GEO1" the authors provided observations and analysis of GPS measurements from the geosynchronous orbit. Noted in the observations were signatures of ionospheric delay and L1 antenna group delay unique to users above LEO. Further analysis of the measurement data has led to a proposed ionospheric delay model for single frequency GPS space users as well as preliminary models of L1 antenna group delay.

This paper will 1) briefly summarize earlier work in the use of GPS above the terrestrial and LEO regime, 2) present and discuss analysis of observed GPS ionospheric delay and L1 antenna group delay from the GEO regime, and 3) compare the observed delay with proposed single frequency ionosphere delay models. This paper will focus on the ionospheric delay modeling solutions for single frequency space users of GPS. Further discussion of L1 antenna group delay modeling will be covered in a follow-on report. [View Full Paper]

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AAS 14-034

ELASTIC MODEL TRANSITIONS: A HYBRID APPROACH UTILIZING QUADRATIC INEQUALITY CONSTRAINED LEAST SQUARES (LSQI) AND DIRECT SHAPE MAPPING (DSM)

Robert J. Jurenko,[*] T. Jason Bush[†] and John A. Ottander[‡]

A method for transitioning linear time invariant (LTI) models in time varying simulation is proposed that utilizes both quadratically constrained least squares (LSQI) and Direct Shape Mapping (DSM) algorithms to determine physical displacements. This approach is applicable to the simulation of the elastic behavior of launch vehicles and other structures that utilize multiple LTI finite element model (FEM) derived mode sets that are propagated throughout time. The time invariant nature of the elastic data for discrete segments of the launch vehicle trajectory presents a problem of how to properly transition between models while preserving motion across the transition. In addition, energy may vary between flex models when using a truncated mode set. The LSQI-DSM algorithm can accommodate significant changes in energy between FEM models and carries elastic motion across FEM model transitions. Compared with previous approaches, the LSQI-DSM algorithm shows improvements ranging from a significant reduction to a complete removal of transients across FEM model transitions as well as maintaining elastic motion from the prior state. [View Full Paper]

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AAS 14-035

PREDICTION OF LIMIT CYCLES USING DESCRIBING FUNCTION ANALYSIS AND THE LUGRE FRICTION MODEL

Ashley Moore,[*] Russel W. Benson,[†] Alison S. Kremer[‡] and Richard M. Dolphus[§]

Understanding friction is essential for simulating engineering systems and designing effective controllers to stabilize them. For some systems, simple friction models with Coulomb and viscous friction are sufficient. In other cases, more advanced dynamic friction models, such as the Dahl model or LuGre model, are necessary to account for memory-dependent phenomena. Unexpected interactions between friction and the system controller can lead to undesirable behavior such as a limit cycle. Such behavior can be understood and even mitigated using describing function analysis. A describing function is the complex ratio of the fundamental harmonic component of the output of a nonlinear element to a sinusoidal input. This paper demonstrates a procedure for obtaining the describing function for both Dahl and LuGre friction models. In classic describing function analysis, the describing function and the closed loop transfer function representing the linear components of the system are visualized together on a Nyquist plot and intersections indicate potential limit cycles. As is demonstrated here, it is possible to generate a modified describing function that is plotted with the open loop transfer function on a Nichols plot of magnitude versus phase. Conducting the analysis using a Nichols plot provides intuitive guidance on how the controller should be adjusted to mitigate potential limit cycles. Both describing function methods are tested on an example system with the LuGre friction model, successfully predicting the limit cycles seen in simulation. The open loop describing function method is then used to guide the redesign of the controller, removing the limit cycle. [View Full Paper]

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AAS 14-037

MODEL-BASED CONTROL FOR ATMOSPHERIC GUIDED ENTRY

Enrico Canuto* **and Marcello Buonocore†**

The paper describes a reference path-tracking algorithm for the compensation of atmospheric and aerodynamic dispersion during the atmospheric entry of a low lift-to-drag interplanetary vehicle. The paper focuses on the longitudinal control. Lateral control is briefly mentioned. Attitude control has been presented elsewhere. The algorithm follows the Embedded Model Control methodology and is based on the real-time estimation and cancellation of the causes that stray the vehicle path from the reference trajectory. The real-time control modulates the vertical component of the lift in order to drive the vehicle fourth-order longitudinal dynamics. To simplify the control structure, longitudinal dynamics is decomposed in a series of two second-order dynamics. The upstairs dynamics (flight path angle and altitude) is commanded by the lift vertical component, the downstairs dynamics (velocity and downrange) is driven by altitude modulation. Arranging the control algorithm in a hierarchical manner becomes straightforward. Control algorithms have been tested by Monte Carlo simulations on a high fidelity six degrees-of-freedom simulator showing that the control approach provides acceptable residual dispersion at the parachute deployment point. [View Full Paper]

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AAS 14-038

SPACE LAUNCH SYSTEM ASCENT FLIGHT CONTROL DESIGN

Jeb S. Orr,[*] John H. Wall,[†] Tannen S. VanZwieten[‡] and Charles E. Hall[§]

A robust and flexible autopilot architecture for NASA's Space Launch System (SLS) family of launch vehicles is presented. The SLS configurations represent a potentially significant increase in complexity and performance capability when compared with other manned launch vehicles. It was recognized early in the program that a new, generalized autopilot design should be formulated to fulfill the needs of this new space launch architecture. The present design concept is intended to leverage existing NASA and industry launch vehicle design experience and maintain the extensibility and modularity necessary to accommodate multiple vehicle configurations while relying on proven and flight- tested control design principles for large boost vehicles.

The SLS flight control architecture combines a digital three-axis autopilot with traditional bending filters to support robust active or passive stabilization of the vehicle's bending and sloshing dynamics using optimally blended measurements from multiple rate gyros on the vehicle structure. The algorithm also relies on a pseudo-optimal control allocation scheme to maximize the performance capability of multiple vectored engines while accommodating throttling and engine failure contingencies in real time with negligible impact to stability characteristics. The architecture supports active in-flight disturbance compensation through the use of nonlinear observers driven by acceleration measurements. Envelope expansion and robustness enhancement is obtained through the use of a multiplicative forward gain modulation law based upon a simple model reference adaptive control scheme. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL HARDWARE

SESSION IV

Many programs depend on heritage, but the future is advanced by those willing to design and implement new and novel architectures and technologies to solve the GN&C problems. This session was open to papers with topics concerning GN&C hardware ranging from theoretical formulations to innovative systems and intelligent sensors that will advance the state of the art, reduce the cost of applications, and speed the convergence to hardware, numerical, or design trade solutions. **Note**: Advances in software applications are covered in *Session III, Advances in GN&C Software*.

National Chairpersons:

Stephen "Phil" Airey
ESA TEC-ECC

Tooraj Kia
NASA / JPL

John Wirzburger
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Local Chairpersons:

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The following paper was not available for publication:

AAS 14-043
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 14-044, -046, -049, and -050

AAS 14-041

ASTRIX®1000 SERIES: THE BEST OF THE FOG TECHNOLOGY FOR SATELLITES

Gilbert Cros,[*] Jean-Jacques Bonnefois,[†] Steeve Kowaltschek[‡] and Guillaume Delavoipiere[§]

In the early 2000s, AIRBUS Defense and Space SAS (formerly ASTRIUM SAS) in collaboration with a French SME, IXSPACE, has developed, with CNES and ESA support, a family of inertial reference units (IRU) for a large range of space applications. These fully European products, called "ASTRIX®," are based on solid-state FOG technology. They have demonstrated excellent results and robustness in orbit has been confirmed. On PLEAIDES Earth observation satellites, ASTRIX 200 products are demonstrating outstanding inertial performances.

AIRBUS D&S and IXSPACE, taking benefit of ASTRIX success, are now developing a new family of ASTRIX products called ASTRIX 1000 series. They will benefit of all advantages of the FOG technology for space applications, in particular low noise, high resolution, high reliability, no life limited items and low consumption. ASTRIX 1000 unit is a compact single box non-redundant unit implementing 3 orthogonal gyroscopic axes and (in option) 3 accelerometric axes. ASTRIX 1090 units are particularly dedicated to mid-level performance applications such as Telecom platforms and will be implemented on ASTRIUM EUROSTAR3000 platform. ASTRIX 1120 units are very similar to ASTRIX 1090 but intended for higher performance applications. While first ASTRIX generation design was performance driven, the objective of this new family is to provide cost effective solutions for satellites, cruise vehicles and landers modules while still proposing medium to high inertial performances.

Innovative architectural design and technological solutions have allowed to reduce significantly production cost while still proposing high inertial performances. This paper, after a presentation of the ASTRIX 1000 products, focuses on these innovations and their implementation. [View Full Paper]

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TARGET RELATIVE NAVIGATION RESULTS FROM HARDWARE-IN-THE-LOOP TESTS USING THE SINPLEX NAVIGATION SYSTEM

Stephen Steffes,[1] Michael Dumke,[2] David Heise,[2] Marco Sagliano,[2] Malak Samaan,[2] Stephan Theil,[3] Erik Boslooper,[4] Han Oosterling,[5] Jan Schulte,[6] Daniel Skaborn,[7] Stefan Söderholm,[8] Simon Conticello,[9] Marco Esposito,[10] Yuriy Yanson,[11] Bert Monna,[12] Frank Stelwagen[12] and Richard Visee[13]

The goal of the SINPLEX project is to develop an innovative solution to significantly reduce the mass of the navigation subsystem for exploration missions which include landing and/or rendezvous and capture phases. The system mass is reduced while still maintaining good navigation performance as compared to a conventional modular system. This is done by functionally integrating the navigation sensors, using micro- and nanotechnology to miniaturize electronics and fusing the sensor data within a navigation filter to improve navigation performance. A breadboard system was build including a navigation computer, IMU, laser altimeter/range finder, star tracker and navigation camera and has space for the redundant counterparts. Testing using the TRON hardware-in- the-loop testbench is ongoing. This aper covers some key design properties of the built system and presents some initial performance results of the hardware-in-the-loop tests. [View Full Paper]

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AAS 14-045

TECHNOLOGY DEVELOPMENT OF BACKSIDE ILLUMINATED CMOS IMAGE SENSORS FOR MEDIUM ACCURACY STAR TRACKER APPLICATIONS

R. Winzenread,[*] R. Jerome,[†] S. Hong,[†] D. Price,[†]
R. Zhu,[‡] P. Levine,[‡] J. Tower,[‡] M. Sileo[§] and E. Tchilian[§]

ON Semiconductor's 0.18μm process technology has been chosen as the platform for development of CMOS image sensors for use in Medium Accuracy Star Tracking (MAST) applications. The project is funded in part by US Government Title-III to develop STELLAR: Staring Technology for Enhanced Linear Line-of-site Angular Recognition, which is a backside illuminated (BSI) focal plane array (FPA). The project is a collaboration between ON Semiconductor, SRI International, and Ball Aerospace & Technologies Corp. The project consists of developing a portfolio of specialized pixels to enable designs of high performance CMOS image sensors for space and military applications. The first image sensing chip will have a resolution of 1 mega pixel, include a 16-bit on-chip ADC, allow either rolling or global shutter operation, and be radiation tolerant for space applications.

This paper discusses the basic architecture of the star tracker sensor and describes the operation and advantages of the integrated CMOS image sensor. A brief overview of the 0.18μm CMOS process and the customization to enable an optimized pixel performance is presented. We present the target specifications followed by a discussion of the trade-offs considered when developing the process and design for MAST applications. We discuss how the design of the epi and BSI process impact important imaging features and ultimately affect MAST performance goals. [View Full Paper]

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STANDARD BOARD HOSTED IN THE ACS COMPUTER FOR CENTRALIZED STARTRACKER CONTROL ELECTRONICS, PROVIDING IMPROVED SIZE, WEIGHT, COST, AND POWER CHARACTERISTICS AND ADAPTABLE TO MULTI-PLATFORM SATELLITES

Dave Jungkind,[*] Franco Boldrini[†] and Paul Murray[‡]

This paper describes improvements to star tracker architecture, originally developed for a high volume constellation program which, through a “plug-and- play” configuration to existing ACS computers, enables an easier adoption across a wide range of satellite platforms and satellite manufactures. The results of this work demonstrates positive improvements in satellite design including: higher level integration for star tracker functions, significant size weight and power benefits (no dedicated mechanical housing for the Electronic Unit, no dedicated DC/DC Converter, all “internal” interfaces via PCI Bus with relevant savings on cabling, etc.), and the ability to incorporate unique program requirements with minimal NRE. Descriptions of architecture enhancements and standardizations are described and results in terms of cost, size, weight, and power are provided. [View Full Paper]

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‡ Director, Reconfigurable Processing, SEAKR Engineering, 6221 S. Racine Circle, Centennial, Colorado 80111, U.S.A.

AAS 14-048

MINIATURE CONTROL MOMENT GYROSCOPE DEVELOPMENT

Erik Mumm,[*] Kiel Davis, Matt Mahin, Drew Neal and Ron Hayes

Honeybee Robotics Spacecraft Mechanisms Corporation has developed multiple Control Moment Gyroscope (CMG) products suitable for small spacecraft. Through the past 3 years we have brought three products online, a standalone CMG, control electronics capable of supporting a 4 CMG array, and a scissored-pair CMG which offers torque about a fixed axis but delivers significantly more specific torque than reaction wheels. The control electronics are capable of driving 4 CMGs and executing the steering law to synthesize individual actuator commands from a torque triple or torque quaternion command. This paper will discuss the demonstrated performance of the systems. [View Full Paper]

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ADAPTIVE AND OPTIMAL CONTROL

SESSION V

This session focussed on novel applications of adaptive or optimal control. When seeking to apply adaptive or optimal control approaches to a specific application, an algorithm must be selected, tailored, and/or redesigned such that it is suitable for the system under consideration and can meet or exceed industry standards with respect to performance and robustness. Session topics focus on the development and/or application of adaptive and optimal control concepts for real systems demonstrating appreciable improvements over the baseline design. Authors were encouraged to provide comprehensive analysis and discussion supported by test data in a laboratory or field environment.

National Chairpersons:

Bradley Moran
Charles Stark Draper Laboratory

Tannen VanZwieten
NASA Marshall
Space Flight Center

Local Chairpersons:

Tim Bevacqua
Lockheed Martin
Space Systems Company

Dan Motooka
Lockheed Martin
Space Systems Company

Mike Ruth
Orbital Sciences Corp.

The following paper numbers were not assigned:

AAS 14-053 to -055, -058 to -060

SPACE LAUNCH SYSTEM IMPLEMENTATION OF ADAPTIVE AUGMENTING CONTROL

John H. Wall,[*] Jeb S. Orr[†] and Tannen S. VanZwieten[‡]

Given the complex structural dynamics, challenging ascent performance requirements, and rigorous flight certification constraints owing to its manned capability, the NASA Space Launch System (SLS) launch vehicle requires a proven thrust vector control algorithm design with highly optimized parameters to provide stable and high-performance flight. On its development path to Preliminary Design Review (PDR), the SLS flight control system has been challenged by significant vehicle flexibility, aerodynamics, and sloshing propellant. While the design has been able to meet all robust stability criteria, it has done so with little excess margin. Through significant development work, an Adaptive Augmenting Control (AAC) algorithm has been shown to extend the envelope of failures and flight anomalies the SLS control system can accommodate while maintaining a direct link to flight control stability criteria such as classical gain and phase margin. In this paper, the work performed to mature the AAC algorithm as a baseline component of the SLS flight control system is presented. The progress to date has brought the algorithm design to the PDR level of maturity. The algorithm has been extended to augment the full SLS digital 3-axis autopilot, including existing load-relief elements, and the necessary steps for integration with the production flight software prototype have been implemented. Several updates which have been made to the adaptive algorithm to increase its performance, decrease its sensitivity to expected external commands, and safeguard against limitations in the digital implementation are discussed with illustrating results. Monte Carlo simulations and selected stressing case results are also shown to demonstrate the algorithm's ability to increase the robustness of the integrated SLS flight control system. [View Full Paper]

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AAS 14-052

ADAPTIVE AUGMENTING CONTROL FLIGHT CHARACTERIZATION EXPERIMENT ON AN F/A-18

Tannen S. VanZwieten,[*] Eric T. Gilligan,[†] John H. Wall,[‡] Jeb S. Orr,[§] Christopher J. Miller[**] and Curtis E. Hanson[††]

The NASA Marshall Space Flight Center (MSFC) Flight Mechanics and Analysis Division developed an Adaptive Augmenting Control (AAC) algorithm for launch vehicles that improves robustness and performance by adapting an otherwise well-tuned classical control algorithm to unexpected environments or variations in vehicle dynamics. This AAC algorithm is currently part of the baseline design for the SLS Flight Control System (FCS), but prior to this series of research flights it was the only component of the autopilot design that had not been flight tested. The Space Launch System (SLS) flight software prototype, including the adaptive component, was recently tested on a piloted aircraft at Dryden Flight Research Center (DFRC) which has the capability to achieve a high level of dynamic similarity to a launch vehicle. Scenarios for the flight test campaign were designed specifically to evaluate the AAC algorithm to ensure that it is able to achieve the expected performance improvements with no adverse impacts in nominal or near-nominal scenarios. Having completed the recent series of flight characterization experiments on DFRC's F/A-18, the AAC algorithm's capability, robustness, and reproducibility, have been successfully demonstrated. Thus, the entire SLS control architecture has been successfully flight tested in a relevant environment. This has increased NASA's confidence that the autopilot design is ready to fly on the SLS Block I vehicle and will exceed the performance of previous architectures. [View Full Paper]

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AAS 14-056

INITIAL AND FEEDBACK SOLUTIONS FOR ORBITAL PURSUIT EVASION USING A HOMOTOPY METHOD

William T. Hafer,* Helen L. Reed,† James D. Turner‡ and Khanh Pham§

A homotopy technique for solving the orbital pursuit evasion problem is shown. The method is based on an analytical solution to the problem in a zero-gravity environment. A homotopy method is then used to obtain the desired solution in full gravity. Additional homotopy strategies can also be used. In particular, we show a feedback implementation obtained by performing homotopies in the system states over short time steps. When successful, the method is many times faster than alternative methods that rely on expensive optimization techniques. The limitation of the method is that the solution traversal mechanism cannot cross over barrier surfaces, where the solution is discontinuous. Techniques accounting for this limitation are the subject of future work. [View Full Paper]

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§ Senior Aerospace Engineer, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico 87116, U.S.A. E-mail: afrl.rvsv@kirtland.af.mil.

AAS 14-057

A* PATHFINDING FOR CONTINUOUS-THRUST TRAJECTORY OPTIMIZATION

Nathan L. Parrish*

In this paper, a new approach to continuous-thrust trajectory optimization is proposed. By discretizing the orbital state space into discrete nodes, new optimization methods are enabled. The A* algorithm, commonly used to find the optimal path between two points on a two-dimensional map, is used here to find near-optimal paths through the orbital state space. The result is a trajectory modeled as a series of discrete impulses at discrete nodes. Trajectories found using this method are compared to an established tool based on the Sims-Flanagan method which models continuous-thrust trajectories as series of impulsive burns in a continuous state space. [View Full Paper]

* Graduate Research Assistant and member of Colorado Center for Astrodynamics Research, Aerospace Engineering Sciences, University of Colorado at Boulder, 431 UCB, Boulder, Colorado 80309, U.S.A.

CUBESATS AND SMALLSATS

SESSION VI

Cubesats and smallsats range in mass from less than 1 kg up to 180 kg, and are gaining in popularity and utility. At the high end of this mass range, 100 to 180 kg ESPA-class spacecraft are now trusted platforms for missions and offer pointing accuracy, pointing stability, and position knowledge that is compatible with Earth science missions. At the cubesat end of the spectrum the GN&C capabilities are advancing quickly in an effort to support science and technology development missions. This session was open to papers covering both hardware and software aspects of smallsat and cubesat GN&C. Papers on technology development for GN&C and mission GN&C experience were also included.

National Chairpersons:

David Geller
Utah State University
Space Dynamics Laboratory

Bruce Yost
NASA

Local Chairpersons:

Michael Epstein
Lockheed Martin
Space Systems Company

Reuben Rohrschneider
Ball Aerospace & Technologies
Corp.

The following paper numbers were not assigned:

AAS 14-069 to -070

AAS 14-061

THREE-DEGREE-OF-FREEDOM TESTING OF ATTITUDE DETERMINATION AND CONTROL ALGORITHMS ON EXOPLANETSAT

Christopher M. Pong,* Sara Seager† and David W. Miller‡

ExoplanetSat is a 10×10×34-cm, 4-kg space telescope designed to detect exoplanets around bright, Sun-like stars via the transit method. Achieving this science objective necessitates arcsecond-level pointing control, a requirement that has not yet been demonstrated on a CubeSat due to severe mass, volume, and power constraints. This requirement will be achieved by employing a two-stage control architecture that utilizes reaction wheels, desaturated by magnetorquers, to provide coarse rigid-body attitude control and a piezo stage that translates the focal plane orthogonal to the boresight to provide fine line-of-sight pointing control. A three-degree-of-freedom air bearing testbed with flight-equivalent hardware has been designed and fabricated to demonstrate the attitude estimation and control algorithms in closed loop. Results from this hardware testbed will be presented, which demonstrate the camera initialization, slewing, target acquisition, and high-precision pointing modes of ExoplanetSat. In addition, the practical challenges and lessons learned while operating the testbed will be discussed. [View Full Paper]

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FORMULATION OF A SMALL SPACECRAFT AVIONICS TESTBED

Matt Sorgenfrei,* Matt Nehrenz,† Robert Edwards‡ and Sanjay Joshi§

Small spacecraft are increasingly being considered for scientific missions in low Earth orbit and beyond, however these small platforms suffer from less flight heritage than their larger counterparts. In particular, new missions will require advanced guidance, navigation, and control (GNC) capabilities, an area of active research and development for small spacecraft. Successful implementation of advanced GNC technologies in smaller spacecraft requires additional testing, verification, and validation, which in turn places greater pressure on the mission schedule. In an effort to reduce both system-level risk and schedule pressure, a new facility is under development at NASA Ames Research Center. This lab, known as the Generalized Nanosatellite Avionics Testbed (G-NAT), accelerates the development of avionics subsystems for small spacecraft through hardware characterization, software development, and testing of GNC components. This paper will present an overview of the sensors, actuators, and processors that are currently being tested in the G-NAT lab, and will present a case study of a simple single-axis hardware characterization problem. [View Full Paper]

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AERODYNAMIC ATTITUDE AND ORBIT CONTROL CAPABILITIES OF THE ∆DSAT CUBESAT

Josep Virgili Llop,[*] Peter C. E. Roberts[†] and Zhou Hao[‡]

∆Dsat is a 2 unit CubeSat that will be part of the QB50 mission. ∆Dsat has the will study rarefied gas aerodynamics with a payload consisting of 4 steerable fins, each with an area of 408 cm^2. The rotation of these fins can be performed independently and allows these aerodynamic surfaces to change their orientation with respect to the CubeSat body. This gives ∆Dsat the capability to change the amount of drag and lift that it creates and therefore the ability to create aerodynamic torques in any direction (pitch, roll and yaw). These capabilities will be used to perform demonstrations of the use of aerodynamics to actively control the attitude and the orbit of the CubeSat. ∆Dsat will demonstrate aerostable attitude control and re-entry point targeting by drag control. Using realistic simulations it is shown that ∆Dsat aerostability should be able to keep the CubeSat aligned with the flow with an error less than 3°. Also, simulations show that the predicted re-entry ellipse is small enough when targeting Cranfield University so that some of the UK ground stations should be able to pick the ∆Dsat during the last stages of its decay and hence confirm the validity of the technique. [View Full Paper]

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POINTING STABILITY FOR THE DOPPLER WIND AND TEMPERATURE SOUNDER MICROSATELLITE DEMONSTRATION MISSION

William Frazier,[*] Reuben R. Rohrschneider,[†]
Shane Roark[‡] and Larry L. Gordley[§]

The Doppler Wind and Temperature Sounder (DWTS) instrument uses a wide FOV sensor to measure Doppler shifts due to the orbital motion to profile atmospheric temperature from the troposphere into the thermosphere. The sample time for the sensor is 1 second during which the sensor must maintain the vertical line-of-sight stability to within 960 micro-radians, making pointing stability an important factor when considering the platform for a demonstration mission. To keep costs low while providing the necessary orbital platform, a microsat was selected and designed to meet the pointing stability requirements. While this pointing stability is well within the capabilities of conventional spacecraft, it is somewhat challenging for space vehicles based on cubesat hardware. The DWTS microsatellite design is based on Cubesat components, and meets the sensor pointing requirements while costing a fraction of the cost of a typical small satellite with a dedicated launch. The preliminary system design is described, and the results of the attitude control analysis are presented. [View Full Paper]

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AAS 14-065

ADVANTAGES OF SMALL SATELLITE CARRIER CONCEPTS FOR LEO/GEO INSPECTION AND DEBRIS REMOVAL MISSIONS

David K. Geller,* Derick Crocket,† Randy Christensen‡ and Adam Shelley§

This paper focuses on two important types of space missions: inspection LEO/GEO high-value assets to detect and/or resolve anomalies, and LEO/GEO debris disposal missions to reduce space hazards. To demonstrate the efficiency of using reusable SmallSats, two mission architectures are analyzed: 1) a SmallSat Carrier-based system with an in-space refueling capability, and 2) a traditional Carrier-less SmallSat. For each architecture the number of potential SmallSat satellite inspection and debris disposal mission sorties is determined as a function of the initial launch mass.
[View Full Paper]

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AAS 14-066

PROX-1: AUTOMATED TRAJECTORY CONTROL FOR ON-ORBIT INSPECTION

Sean Chait* and David A. Spencer†

The Georgia Institute of Technology Prox-1 mission will demonstrate automated trajectory control in low-Earth orbit relative to a deployed three-unit (3U) CubeSat, for an on-orbit inspection application. Passive thermal imaging provides the basis for an advanced relative navigation system to provide precise relative state estimation and control. Trajectory control is made possible through the use of an agile control moment gyro unit and a 1U hydrazine thruster. Automated maneuver planning and execution utilizes a guidance algorithm based on Artificial Potential Functions. This coupled with Prox-1's extensive control laws creates a robust platform for relative position station-keeping and observation maneuvers. Funded by the Air Force Office of Scientific Research/Air Force Research Laboratory through the University Nanosatellite Program-7, Prox-1 is scheduled to launch in August 2015 as a secondary payload on the Space Test Program-2 launch. [View Full Paper]

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AAS 14-067

SPIN-ASSISTED ANGLES-ONLY NAVIGATION AND CONTROL FOR SMALLSATS

Randy Christensen[*] and David K. Geller[†]

This work analyzes the ability to estimate and control the relative position and velocity of a Small Satellite with respect to a target vehicle using a single optical camera. Although the target range is generally unobservable when using angles-only measurements, relative position/velocity observability can be achieved when the SmallSat is slowly rotating and the camera is offset from the center of gravity. The sensitivity of the navigation errors and trajectory dispersions to several simulation parameters is discussed, including SmallSat camera offset, spin rate, and range to target. Also included in the analysis is the effect of common sensor errors (e.g. camera and gyro bias/noise), external disturbances, and initial conditions. Future efforts are mentioned to extend the analysis to cooperative/uncooperative targets and to increase analysis efficiency through Linear Covariance analysis. [View Full Paper]

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AAS 14-068

DICE: CHALLENGES OF SPINNING CUBESATS

Tim Neilsen,[*] Cameron Weston,[†] Chad Fish[‡] and Bryan Bingham[§]

Funded by the NSF CubeSat and NASA ELaNa programs, the DICE mission consists of two 1.5U CubeSats which were launched into an eccentric low Earth orbit on October 28th, 2011. Each identical spacecraft carries a suite of ionospheric space weather payloads. The use of two identical CubeSats, at slightly different orbiting velocities in nearly identical orbits, permits the deconvolution of spatial and temporal ambiguities in the observations of the ionosphere from a moving platform. Deployable wire booms require each CubeSat to be spin stabilized. Attitude determination and control are accomplished using magnetometers, a sun sensor, and torque coils. Position and time are provided by GPS.

DICE has greatly advanced nano-satellite based mission capabilities, demonstrating constellation science and opening up a number of groundbreaking technologies to the CubeSat community. DICE has made many co-incident observations of ionospheric structure and is the first CubeSat mission to observe field-aligned currents in the ionosphere. In this paper we will review the on-orbit performance of the DICE ADCS design as well as communications/GPS antenna issues associated with a spinning CubeSat.
[View Full Paper]

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HOSTED PAYLOADS

SESSION VII

This session provided an overview of the emerging paradigm for delivering and operating payloads on rides of opportunity. Both the DoD and NASA have major initiatives focused on leveraging hosted payload opportunities to enhance access and affordability. The session covered the players, the benefits and challenges, the technical requirements, experiences, and the GN&C considerations.

National Chairpersons:	David Anhalt Iridium-Prime
	Prasun Desai NASA Headquarters
Local Chairpersons:	Bill Frazier Ball Aerospace & Technologies Corp.
	Paul Graven Cateni

The following paper was not available for publication:

AAS 14-073

“The TEMPO Mission: It’s About Time!,” Brian Baker, Laura Hale, Dennis Nicks, Kenton Lee (Ball), Kelly Chance, Ziong Liu, Raid Sulieman (Smithsonian Astrophysical Observatory), Jim Carr, (Carr Astro), David Flittner, Jassim Al-Saadi, Wendy Pennington, Alan Little, David Rosenbaum (NASA/LRC) (Presentation Only)

The following paper numbers were not assigned:

AAS 14-074, -076 to -080

UPDATE ON COMMERCIALLY HOSTED PAYLOADS INCLUDING THE IRIDIUM PRIME^{SM} PAYLOAD ACCOMMODATION SERVICE

David A. Anhalt*

The purpose of this paper is to characterize the trend within government departments and agencies toward greater use of commercially hosted payloads. This shift in government customer demand represents a turning point in the convergence of commercial, civil and national security space sectors. Early successes using this approach have led to landmark policy decisions on the part of the U.S. Government to further employ the hosted payload business approach for satisfying government needs for space goods and services. The paper recounts the early achievements by commercially hosted payloads, recent policy reforms that further enable use of commercial hosted solutions, and actions directed by Congress to speed up the use of this new business approach. The paper concludes with a description of Iridium PRIME^{SM}, the world's first turnkey space payload accommodation service. [View Full Paper]

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AAS 14-072

EARTH OBSERVATIONS FROM THE INTERNATIONAL SPACE STATION: THE TELEDYNE "MULTIPLE USER SYSTEM FOR EARTH SENSING" (MUSES)

Mark S. Whorton[*] and Olawale Adetona[†]

The International Space Station (ISS) is a unique and enabling asset for remote sensing to support many classes of Earth science investigations, commercial Earth observations and humanitarian aid. To more fully utilize the potential of ISS for Earth remote sensing, Teledyne is developing the Multiple User System for Earth Sensing (MUSES), an inertially stabilized platform enabling Earth surface target pointing and tracking with multiple, advanced imaging systems. [View Full Paper]

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AAS 14-075

HOSTING THE DEEP SPACE ATOMIC CLOCK (DSAC) ON THE ORBITAL TEST BED (OTB-1) SATELLITE

F. Brent Abbott,* William Thompson* and Todd A. Ely†

This paper will share the experiences, ongoing work and lessons learned in hosting the DSAC instrument on a relatively standard satellite bus, OTB-1. As DSAC is a great advancement in navigation, this hosting will confirm the on-orbit performance to enable DSAC to be used for future operational systems. Payload performance and operational requirements will be discussed. The process in which JPL and Surrey US work together with requirements and bus design to optimize maximum return on on-orbit testing will be presented with focus on GN&C systems. [View Full Paper]

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SAVING THE SPACECRAFT: RESCUES, FAULT PROTECTION AND LIFE EXTENSIONS

SESSION VIII

Throughout the history of space missions, well-crafted automation and human ingenuity have saved and extended missions. One of the inspirations for this session is the Apollo 13 mission in which the team united to solve a critical problem that rescued the crew. The goal of this session is to gather both historic and modern stories about spacecraft rescues, fault protection design, and life extension efforts.

National Chairpersons:

Frank Geisel
Charles Stark Draper Laboratory

Sam W. Thurman
NASA Jet Propulsion Laboratory

Local Chairperson:

Christy Edwards-Stewart
Lockheed Martin
Space Systems Company

The following paper was not available for publication:

AAS 14-084
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 14-081, -082, -087 to -090

AAS 14-083

SIMPLE SAFE SITE SELECTION: HAZARD AVOIDANCE ALGORITHM PERFORMANCE AT MARS*

Andrew E. Johnson† and Amit B. Mandalia‡

Many scientifically interesting sites at Mars have small-scale hazards that can pose a threat to landers and rovers. Hazard Detection and Avoidance (HDA) can be used during the terminal phase of flight to find and divert to a safe site. An algorithm has been developed that operates directly on a single flash lidar range image and is able to rapidly select a safe site in a computationally efficient manner. A flash lidar simulator is used to analyze the performance of the algorithm relative to the terrain and vehicle. The algorithm is able to select a safe site with confidence for terrains with rock abundances up to 35% and slopes up to the capability of the selected rover (22°). Variation in altitude, attitude, and lidar noise do not significantly affect the performance of the safe site selection. This hazard avoidance algorithm can decrease landing failures at all the landing sites listed in the Mars 2020 Science Definition Report, and has the potential to operate at far more difficult sites. [View Full Paper]

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* This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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AAS 14-085

HAYABUSA - ASTEROID SAMPLE RETURN THROUGH HARDSHIPS DURING ITS SEVEN YEARS ROUND-TRIP VOYAGE

Junichiro Kawaguchi*

This paper describes what and how the Hayabusa project team performed its seven years voyage through many hardships, focusing its attention on the astrodynamics aspects. [View Full Paper]

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AAS 14-086

FAULT RECOVERY STRATEGIES FOR AUTONOMOUS PARAFOILS

Matthew R. Stoeckle,[*] Amer Fejzic,[†] Louis S. Breger[†] and Jonathan P. How[‡]

Guided airdrop, or autonomous parafoil, systems are used to accurately deliver payload to a desired location. This aerial delivery method provides a safety and logistical advantage over traditional ground- or helicopter-based payload transportation methods. Faults that occur in-flight can increase the target miss distance to unacceptable levels, resulting in a mission failure. This paper presents recovery strategies designed to mitigate the effects of several common faults and allow for a successful mission even with severe loss of control authority. For flights in which a fault occurs, an extensive, high-fidelity Monte Carlo simulation study demonstrates a miss distance requirement satisfaction rate of 84.5% for cases in which recovery strategies are implemented versus 21% for cases with the nominal guidance strategy. Flight tests results consistent with earlier simulations show successful detection and isolation of faults as well as implementation of recovery strategies that result in miss distances comparable to those from healthy flights. [View Full Paper]

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ORION MULTI-PURPOSE CREW VEHICLE GUIDANCE, NAVIGATION AND CONTROL

SESSION IX

This session highlighted the recent Guidance, Navigation and Control developments for the Orion Multi-Purpose Crew Vehicle (MPCV) from the Exploration Flight Test 1 (EFT-1), scheduled to launch in December 2014, and demonstrated the system capability to perform a high-energy entry, to the Exploration Missions that will take the Orion MPCV and Crew beyond Earth orbit. The papers in this session overview the Orion system from the launch abort capabilities and navigation systems to future exploration mission concepts and design references.

National Chairpersons:

Tim Straube
NASA Johnson Space Center

Chris D'Souza
NASA Johnson Space Center

Local Chairperson:

Daniel G. Kubitschek
Lockheed Martin
Space Systems Company

The following paper numbers were not assigned:

AAS 14-098 to -100

AAS 14-091

FULL-ENVELOPE LAUNCH ABORT SYSTEM PERFORMANCE ANALYSIS METHODOLOGY

Vanessa V. Aubuchon*

The implementation of a new dispersion methodology is described, which disperses abort initiation altitude or time along with all other Launch Abort System (LAS) parameters during Monte Carlo simulations. In contrast, the standard methodology assumes that an abort initiation condition is held constant (e.g., aborts initiated at altitude for Mach 1, altitude for maximum dynamic pressure, etc.) while dispersing other LAS parameters. The standard method results in large gaps in performance information due to the discrete nature of initiation conditions, while the full-envelope dispersion method provides a significantly more comprehensive assessment of LAS abort performance for the full launch vehicle ascent flight envelope and identifies performance "pinch-points" that may occur at flight conditions outside of those contained in the discrete set. The new method has significantly increased the fidelity of LAS abort simulations and confidence in the results. [View Full Paper]

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AAS 14-092

ORION EXPLORATION FLIGHT TEST-1 (EFT-1) ABSOLUTE NAVIGATION DESIGN

Jastesh Sud,[*] Robert Gay,[†] Greg Holt[‡] and Renato Zanetti[§]

Scheduled to launch in September 2014 atop a Delta IV Heavy from the Kennedy Space Center, the Orion Multi-Purpose-Crew-Vehicle (MPCV's) maiden flight dubbed "Exploration Flight Test-1" (EFT-1) intends to stress the system by placing the uncrewed vehicle on a high-energy parabolic trajectory replicating conditions similar to those that would be experienced when returning from an asteroid or a lunar mission. Unique challenges associated with designing the navigation system for EFT-1 are presented in the narrative with an emphasis on how redundancy and robustness influenced the architecture. Two Inertial Measurement Units (IMUs), one GPS receiver and three barometric altimeters (BALTs) comprise the navigation sensor suite. The sensor data is multiplexed using conventional integration techniques and the state estimate is refined by the GPS pseudorange and deltarange measurements in an Extended Kalman Filter (EKF) that employs the UDUT decomposition approach. The design is substantiated by simulation results to show the expected performance. [View Full Paper]

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AAS 14-093

TRANSLATION BETWEEN DISSIMILAR IMU ERROR MODELS TO ENABLE PROPER EKF TESTING AND VALIDATION*

Robert W. Gillis† and Harvey Mamich‡

The Orion Extended Kalman Filter (EKF) and the simulated Orion Inertial Measurement Unit (IMU) model used to verify it were constructed with different models of certain gyroscope and accelerometer errors. While both the filter and the simulated IMU had states to model a complete range gyroscope and accelerometer misalignments and non-orthogonality, individually none of these states in the EKF had a direct match with an equivalent state in the IMU model. This resulted in incorrectly tuned IMU error terms and made it very difficult to evaluate how well the EKF was estimating these parameters. It is shown here that both EKF and the IMU model represent the same space of errors. The difference in error parameters is due to what is the equivalent of a coordinate change. This is shown by the development of a transformation that converts IMU error parameters into the same form as used by the EKF. This transformation is then used to show that the Orion EKF does estimate IMU errors as would be expected given the dynamics during different flight segments. [View Full Paper]

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AAS 14-094

DEFINITION OF THE DESIGN ENTRY TRAJECTORY AND ENTRY FLIGHT CORRIDOR FOR THE NASA ORION EXPLORATION MISSION 1 USING AN INTEGRATED APPROACH AND OPTIMIZATION

Luke W. McNamara* and Jeremy R. Rea†

For NASA's Orion Exploration Mission 1 (EM-1) the Orion spacecraft is being designed to execute a guided skip-entry trajectory. In order to determine the design trajectory, an assessment of the entry flight corridor must first be completed. Defining the flyable entry flight corridor requires taking into account multiple subsystem constraints such as those on guided landing accuracy, service module debris disposal, Human System Interface Requirements, contingency entry modes, and structural loads in addition to flight test objectives. During the EM-1 Design Analysis Cycle 2 design changes occurred, due to mass reduction efforts, that made defining the flyable entry corridor for the EM-1 mission challenging. Approaches to characterize the domain space using discretized independent variables along with polynomial curve fitting of the resulting dependent variables are discussed. This paper describes the techniques, such as grid searches and iterative numerical optimization searches, that were explored to characterize the EM-1 entry flight corridor and define the design entry interface state with respect to key flight test constraints and objectives. [View Full Paper]

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AAS 14-095

NAVIGATION DESIGN AND ANALYSIS FOR THE ORION CISLUNAR EXPLORATION MISSIONS

Christopher D'Souza,* Greg Holt,† Robert Gay‡ and Renato Zanetti§

This paper details the design and analysis of the cislunar optical navigation system being proposed for the Orion Earth-Moon (EM) missions. In particular, it presents the mathematics of the navigation filter. It also presents the sensitivity analysis that has been performed to understand the performance of the proposed system, with particular attention paid to entry flight path angle constraints and the DV performance.
[View Full Paper]

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AAS 14-096

TRAJECTORY DESIGN ANALYSIS OVER THE LUNAR NODAL CYCLE FOR THE MULTI-PURPOSE CREW VEHICLE (MPCV) EXPLORATION MISSION 2 (EM-2)

Jeffrey P. Gutkowski,* Timothy F. Dawn* and Richard M. Jedrey*

The first crewed mission, Exploration Mission 2 (EM-2), for the MPCV Orion spacecraft is scheduled for August 2021, and its current mission is to orbit the Moon in a highly elliptical lunar orbit for three days. A 21-year scan was performed to identify feasible missions that satisfy the propulsive capabilities of the Interim Cryogenic Propulsion Stage (ICPS) and MPCV Service Module (SM). The mission is divided into 4 phases: (1) a lunar free return trajectory, (2) a hybrid maneuver, during the trans-lunar coast, to lower the approach perilune altitude to 100 km, (3) lunar orbit insertion into a 100 x 10,000 km orbit, and (4) lunar orbit loiter and Earth return to a splashdown off the coast of Southern California. Trajectory data was collected for all feasible missions and converted to information that influence different subsystems including propulsion, power, thermal, communications, and mission operations. The complete 21-year scan data shows seasonal effects that are due to the Earth-Moon geometry and the initial Earth parking orbit. The data and information is also useful to identify mission opportunities around the current planned launch date for EM-2. [View Full Paper]

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AAS 14-097

ORION SAMPLE CAPTURE AND RETURN (OSCAR)[*]

John Ringelberg,[†] Reid Hamilton[‡] and Chris Norman[§]

NASA's Orion spacecraft is designed to meet the evolving needs of our nation's deep space exploration program for decades to come1. As an early capability for exploration, Lockheed Martin is developing a design concept for an Orion in-space capture and return of a lunar sample. This paper presents the feasibility, benefits, and a concept of operations of such a mission. The paper focus will be on the rendezvous, approach and capture by Orion of a sample container launched from the lunar surface and delivered to an Earth-Moon Libration point 2 (L2) orbit. The mission design uses Orion baseline capabilities to perform rendezvous and approach to capture of the sample container. Results from preliminary testing of the operations involved with such a mission have been performed in our Space Operations Simulation Center – a full scale, high fidelity relative navigation test facility – and are presented. Finally, extensibility of this mission to a Mars, Mars moon or asteroid mission will be presented. [View Full Paper]

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MIXED ACTUATOR ATTITUDE CONTROL

SESSION X

This session explores the recent renewed community interest in the design and development of spacecraft attitude control systems employing mixed control torque actuators. Such 'hybrid' attitude control systems are of potential utility in cases where, for example, a spacecraft has lost the use of one or more of their reaction wheel set such that there are less than three functional operating reaction wheels remaining. Typically mixed actuator/hybrid attitude control modes are ones in which thrusters or, in some mission applications, magnetic torquers, are operated in tandem with the two remaining healthy reaction wheels to provide three-axis attitude control torques. Mixed actuator attitude control techniques have been successfully implemented in the past on such spacecraft as FUSE and TIMED. To extend their productive mission life several currently flying spacecraft are currently considering the use of mixed actuator modes for contingency attitude control in the face of reaction wheel failures suffered on-orbit. The papers in this session review the community's historical experience (lessons learned) with contingency mixed actuator/hybrid spacecraft attitude control using only two reaction wheels. The results of more recent mixed actuator design and development work is also addressed by the papers in this session.

National Chairpersons:

Neil Dennehy
NASA
Goddard Space Flight Center

Allan Lee
NASA Jet Propulsion Laboratory

Local Chairperson:

Scott Francis
Lockheed Martin
Space Systems Company

The following paper numbers were not assigned:

AAS 14-108 to -110

SPACECRAFT HYBRID CONTROL AT NASA: A HISTORICAL LOOK BACK, CURRENT INITIATIVES, AND SOME FUTURE CONSIDERATIONS

Neil Dennehy[*]

There is a heightened interest within NASA for the design, development, and flight implementation of mixed-actuator hybrid attitude-control systems for science spacecraft that have less than three functional reaction wheel actuators. This interest is driven by a number of recent reaction wheels failures on aging, but still scientifically productive, NASA spacecraft. This paper describes the highlights of the first NASA Cross-Center Hybrid Control Workshop that was held in Greenbelt, Maryland in April of 2013 under the sponsorship of the NASA Engineering and Safety Center (NESC). A brief historical summary of NASA's past experiences with spacecraft mixed-actuator hybrid attitude control approaches, some of which were implemented inflight, will be provided. This paper will also convey some of the lessons learned and best practices captured at that workshop. Some relevant recent and current hybrid control activities will be described with an emphasis on work in support of a repurposed Kepler spacecraft. Specific technical areas for future considerations regarding spacecraft hybrid control will also be identified. [View Full Paper]

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AAS 14-102

HYBRID CONTROL ARCHITECTURE FOR THE KEPLER SPACECRAFT

Dustin Putnam[*] and Douglas Wiemer[*]

The Kepler spacecraft, which flies in a heliocentric, Earth-trailing, orbit, suffered the failure of one of its four reaction wheels on July 13, 2012. A second wheel failed on May 11, 2013, leaving the spacecraft with only two operational wheels, and thus unable to perform 3-axis control on wheels alone. The spacecraft is equipped with a set of eight reaction control thrusters which can be used for attitude control. This paper discusses a hybrid control architecture where the remaining reaction wheels control the cross-boresight axes of the telescope, the third axis is momentum stabilized, and the instrument boresight is kept in the ecliptic plane to minimize solar pressure torque. Two BATC CT-633 star trackers provide attitude measurements for cross-boresight stability of 0.5 arc-sec 1s. The control architecture documented here enables Kepler to continue collecting high precision, long duration photometric data required for exo-planet research. [View Full Paper]

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AAS 14-103

POINTING AND MANEUVERING A SPACECRAFT WITH A RANK-DEFICIENT REACTION WHEEL COMPLEMENT

Eric Stoneking* **and Ken Lebsock†**

The Kepler spacecraft has suffered two reaction wheel failures, leaving two wheels remaining to perform attitude control. While Kepler may enlist thrusters and solar radiation pressure as control actuators, we investigate two complementary algorithms for controlling a Kepler-like spacecraft using the wheels only. First, we consider the problem of holding an inertial attitude. Some attitude drift in the uncontrolled axis is unavoidable, but a series of two-axis wheel maneuvers may be used to re-center the attitude. We present the performance and limitations of this technique. Second, we consider periodically performing a 180° maneuver to enable passive momentum unloading as a fuel conservation measure. We show that an attitude control law feeding back attitude, attitude rate, and wheel momentum errors may be employed to perform this maneuver while keeping the telescope boresight a safe angle away from the direction of the Sun. [View Full Paper]

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AAS 14-104

PRECISION POINTING FOR A SKEWED 2-REACTION WHEEL CONTROL SYSTEM

Mark Karpenko,* Wei Kang,† Ronald J. Proulx‡ and I. Michael Ross§

This paper addresses the pointing stability of a Kepler-like spacecraft when only two skewed torquers are available to control the vehicle. Conventional wisdom, corroborated by Kalman's theory on linear controllability, suggests that the failed spacecraft is not controllable. Starting with the contrarian view that it may be possible to exploit the nonlinearities and stabilize the failed spacecraft, we propose an approach for assessing the theoretically possible pointing accuracy of the failed system. A key element in this process is the formulation of an infinite-horizon nonlinear optimal control problem. Using pseudospectral (PS) theory and data for the failed Kepler spacecraft, we show that the system can indeed be stabilized around the origin. Motivated by this result, we then design a Lyapunov function to derive a feedback controller as a surrogate for the optimal PS controller. This proxy controller, while not optimal, is implementable on Kepler as the onboard computational requirements are reduced to the computation of two polynomials. We also show that the penalty for the reducing the computational requirement is a potential reduction in performance. [View Full Paper]

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A COLD GAS MICRO PROPULSION SYSTEM AS ACTUATOR OF FINE POINTING AND ATTITUDE CONTROL MISSIONS ON SCIENCE AND EARTH OBSERVATION SATELLITES

F. Boldrini, L. Ceruti, L. Fallerini, G. Matticari, M. Molina, G. Noci,[*] A. Atzei and C. Edwards[†]

A European Cold Gas Micro Propulsion system with the possibility to finely control the generated micro thrust level from 1μN to 1mN has been successfully developed, manufactured and launched on Gaia spacecraft. Following this achievement, two additional Cold Gas Micro Propulsion Systems are currently under fabrication for LISA Pathfinder and Microscope. The paper presents a review of the Cold Gas Micro Propulsion System for current and future missions with tight attitude control requirements, highlighting the state of the art and the major modifications possible to cope with more demanding requirements. The implementation of an Electronic Pressure Regulator is addressed as well, to increase the flexibility and versatility and prepare an optimized 2nd generation product in view of future potential applications also on non-European satellites. [View Full Paper]

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AAS 14-106

HIGH EFFICIENCY MAGNETIC TORQUE BARS (MTBS)

Jim Krebs* and Eric Stromswold†

Magnetic Torquer Bars (MTBs) provide a highly reliable, jitter free method of producing torque to control the attitude of spacecraft and the speed of reaction wheels. MTBs require a small fraction of the power-mass products of air coils. They can be used indefinitely, without the mass expendables of thrusters or the speed, reliability and life limitations of reaction wheels.

In low Earth orbit, medium sized MTBs produce torques comparable to small reaction wheels. Cayuga Astronautics has introduced two extensive lines of standard MTBs ranging from 1 to 800 Am^2: a Long Series and a Short Series. Our simplified, standardized designs minimize the cost and manufacturing lead time and improve product robustness. Long Series MTBs, which have cores with a large aspect ratio, require less power, while the more compact Short Series MTBs provide lower residual moments. All have been optimized to minimize mass and power.

Graphs are provided that compare our designs to our competition. The length of our short MTBs and the power of our long MTBs are generally less than our competition. The mass of both designs are often significantly less than our competition.
[View Full Paper]

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DAWN SPACECRAFT OPERATIONS WITH HYBRID CONTROL: IN-FLIGHT PERFORMANCE AND CERES APPLICATIONS*

Brett A. Smith,† Ryan S. Lim‡ and Paul D. Fieseler§

Dawn is a low-thrust interplanetary spacecraft currently en-route to the asteroid Ceres following a successful 14-month visit to Vesta, to better understand the early creation of the solar system. The Dawn spacecraft uses both reaction wheel assemblies (RWA) and a reaction control system (RCS) to provide 3-axis attitude control for the spacecraft. Reaction wheels were designed to be the primary system for attitude control, however two of the wheels have shown high friction anomalies and have been removed from service. The project has implemented a hybrid control algorithm using two healthy reaction wheels and RCS thrusters to provide the most science return at Ceres.

With only two remaining healthy RWAs, hybrid control became part of the baseline plan for Ceres science operations. There are a number of operational complexities and changes that must be accommodated to make this new control method function effectively in coordination with the desired science observations. Using two RWAs in a hybrid configuration to control two of the three spacecraft axes increases operational complexity. The benefit of the increased complexity is reduced hydrazine use as well as more accurate pointing, when compared to all-RCS control. Hydrazine propellant for the RCS thrusters is the major constraining resource for the Dawn mission, making the hybrid controller very desirable for science acquisition.

This paper discusses Dawn's attitude control flight experiences with hybrid control and planned hybrid control use in Ceres orbit operations. Actual Flight data under hybrid control are presented and compared with simulation predictions. Operational considerations for preparing Dawn to use a hybrid actuator configuration are outlined as well. The discussion also includes the science operational plan for using hybrid control in Ceres orbit. Lastly, some considerations that should be of interest to similar reduced-actuator missions are presented. [View Full Paper]

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HWIL TESTBEDS AND DEMONSTRATION LABORATORIES

SESSION XI

As the complexity of aerospace flight systems continues to rise, increasingly more-elaborate means of system- and subsystem-level testing have become necessary to reduce programmatic risk, thus motivating development of advanced 'test-like-you-fly' HWIL testbeds. Many of these facilities accommodate modular testing of newly developed flight control algorithms, flight software, and flight hardware. In some cases, HWIL testbed laboratories enable a virtual fly-off to be held between competing designs. This session explored capabilities of existing sophisticated, high-fidelity, GN&C laboratories throughout the industry.

National Chairpersons:

Lars Dyrud
Charles Stark Draper Laboratory

James Turner
Texas A&M University

Local Chairpersons:

Jeff Bladt
Ball Aerospace & Technologies Corp.

Michael L. Osborne
Lockheed Martin
Space Systems Company

The following paper was not available for publication:

AAS 14-117
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 14-111, -119 to -120

AAS 14-112

HONEYWELL'S MOMENTUM CONTROL SYSTEM TESTBED

Brian Hamilton*

Spacecraft attitude control using Momentum Control Systems (MCS) based on Control Moment Gyroscopes (CMG) or Reaction Wheel Assemblies (RWA) is one of the most difficult things to demonstrate with ground-based hardware. Honeywell has spent the past decade developing and refining a facility for this purpose in Glendale, Arizona.

The facility features a surrogate spacecraft weighing approximately 3200 lbs (1450 kg) with first flexible mode of approx. 14 Hz. It includes 6 single-gimbal CMGs (engineering units and flight spares – real CMGs), and both ring-laser and fiber optic 3-axis gyro packages. The spacecraft flies without friction on a spherical air bearing in 3 degrees of freedom, with unlimited rotation about the vertical axis, and ±30 degrees about any horizontal axis. A unique, proprietary active mass balance system limits the accumulation of momentum in the gravity field to no more than a few Nms. The vehicle carries several hours of onboard battery power, and features a PowerPC-based onboard computer communicating over wireless with a ground station for commands and telemetry. Realtime code is built from MATLAB Simulink and running in minutes. A wall projection system displays STK imagery allowing demonstration of acquisition and tracking of moving targets using an onboard laser and camera.

Recognizing the appeal such a facility would have in the space community, a modular design approach was employed, making it readily available to guest investigators – friendly to the plug-and-play of alternative actuators, sensors, and software. The facility has already hosted guests and research programs from both government and industry. [View Full Paper]

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SYSTEM LEVEL HARDWARE-IN-THE-LOOP TESTING FOR CUBESATS

Bryan Bingham[*] and Cameron Weston[†]

Funded by the NSF CubeSat and NASA ELaNa programs, the Dynamic Ionosphere CubeSat Experiment (DICE) mission consists of two 1.5U CubeSats which were launched into an eccentric low Earth orbit on October 28, 2011. Each identical spacecraft carries two Langmuir probes to measure ionospheric in-situ plasma densities, electric field probes to measure in-situ DC and AC electric fields, and a magnetometer to measure in-situ DC and AC magnetic fields.

During the design of DICE it was determined that a system-level hardware-in-the-loop (HWIL) test would need to be developed in order to properly test subsystem interactions with the attitude control system. The test would require simulating orbital dynamics, attitude dynamics, and environmental physics such as local magnetic fields. The flight software would need to run on a flight computer and acquire sensor measurements from real sensors which would then be used to command actuator outputs. The outputs from the actuators would need to affect the simulated attitude dynamics to perform closed loop control testing.

In August of 2010 the Space Dynamics Laboratory designed and built the Nanosat Operation Verification & Assessment (NOVA) Test Facility. The primary focus of NOVA was to provide component and system level testing for small satellites with a particular focus on CubeSats. The NOVA Test Facility was ideally positioned to provide the system level HWIL testing required by the DICE Mission. This paper will describe the design, setup, and implementation of the HWIL test performed for the DICE mission. [View Full Paper]

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AAS 14-114

ASTROS: A 5DOF EXPERIMENTAL FACILITY FOR RESEARCH IN SPACE PROXIMITY OPERATIONS

Panagiotis Tsiotras*

In this paper we summarize the technical characteristics of the Autonomous Spacecraft Testing of Robotic Operations in Space (ASTROS) facility at the School of Aerospace Engineering at Georgia Tech. The experimental facility consists of a 5DOF platform supported on hemispherical and linear air-bearings moving over an extremely flat epoxy floor, thus simulating almost friction-free conditions. The ASTROS facility can be used to support the development and testing of autonomous rendezvous and docking (ARD) and other general proximity operations (ProxOps) algorithms. A variety of on-board sensors and actuators allow the testing of most realistic scenarios one may encounter in practice. An overhead VICON system is used to provide baseline truth data for validation purposes. [View Full Paper]

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AAS 14-115

LASR A UNIVERSITY-BASED NATIONAL TESTBED FOR SPACE PROXIMITY OPERATIONS IN AN OPERATIONALLY RELEVANT ENVIRONMENT

James D. Turner,* John L. Junkins† and John E. Hurtado‡

This paper describes a unique research facility at Texas A&M University, the Land, Air, and Space Robotics (LASR) laboratory. LASR provides a capability for high fidelity six degree of freedom relative motion of multiple controlled or uncontrolled platforms. LASR is a testbed intended for experimental research in sensing and control whereby selected sub-systems hardware and software- in-the-loop can be tested in a high-fidelity way, driven by our best simulation of (say) on-orbit dynamics and control systems for a full-up spacecraft, but with selective elements in the simulation replaced by actual hardware and data from live sensing. A main focus is upon sensing systems and the associated algorithms for extracting real-time information for use in real-time control. The thesis underlying LASR is that the "information front end" of many challenging control problems is where the greatest robustness challenges lie, and there is a need for a new kind of laboratory that enables inexpensive advanced research and development to retire risk. LASR is a versatile, highly reconfigurable laboratory where iteration between concepts, algorithms and physical realizations can be performed to find new solutions to difficult problems and enhance maturity/robustness of critical subsystems in a ground-based facility. The current stage of development and recent research thrusts in LASR are discussed. [View Full Paper]

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THE SPACE OPERATIONS SIMULATION CENTER: A 6DOF LABORATORY FOR TESTING RELATIVE NAVIGATION SYSTEMS

Sherri Ahlbrandt,[*] David Huish,[†] Cory Burr[‡] and Reid Hamilton[§]

The Space Operations Simulation Center (SOSC) on the Lockheed Martin campus southwest of Denver Colorado is a sophisticated, high fidelity laboratory designed for testing hardware-in-the-loop relative navigation systems. Using six degree-of-freedom (6DOF) mechanisms, or robots, that precisely maneuver on an ultra-stable pier throughout a large high bay, the SOSC is capable of simulating full scale spacecraft motion relative to another object or point in space. The carrying capacity of the robots and range of motion allow for integration of complete sensor suites and spacecraft systems.

The SOSC has proved to be a unique test environment for a diverse user base such as development teams from NASA centers, space sensor suppliers, internal Lockheed Martin R&D projects and even university senior design teams. Testing has been performed for all phases of project development; from proof of concepts through flight hardware and flight software design and integration. The laboratory supports the evaluation of all the components of relative navigation missions, including passive and active sensors, mechanisms, algorithms, models and software, as well as the integration of these elements into subsystems and systems for development and test-like-you-fly verification. Both closed and open-loop control of the relative robot motion has been implemented in these activities.

This paper gives a brief introduction to the lab and presents the lab's superior capabilities and operational flow by describing some recent test campaigns, major challenges overcome, and the test outcomes. Examples of projects include cross-country remote operations and ongoing closed loop rendezvous and docking maneuvers to a full scale model of an ISS docking port using the STORRM VNS LIDAR from STS-134.
[View Full Paper]

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AAS 14-118

TESTING FACILITY FOR AUTONOMOUS ROBOTICS AND GNC SYSTEMS AT WEST VIRGINIA UNIVERSITY

Thomas Evans,* John Christian,† Giacomo Marani‡ and Patrick Lewis§

West Virginia University (WVU) is home to the West Virginia Robotic Technology Center (WVRTC) – a state-of-the-art testing facility for space robotics and spacecraft guidance, navigation, and control (GNC) systems. The facility was established in 2009 to support the development of technologies for satellite servicing for NASA Goddard Space Flight Center, and is now expanding to address a wider range of issues related to spacecraft GNC. The WVRTC is located in a secure building outside of WVU's main campus and is staffed by full-time research engineers. In its present configuration, the facility consists of a number of test areas. First is a 16.4 x 6.7 m air bearing table equipped with a fully-functional robotic Grapple Arm, a full-scale mock-up of the Orion Multi-Purpose Crew Vehicle (MPCV), and a mock-up of a generic robotic spacecraft which represents a depot or operational site of interest for an astronaut crew. The Grapple Arm was flight qualified for the Hubble Robotic Servicing and De-orbit Mission (HRSDM) and its design is based on the Shuttle Remote Manipulator System (SRMS). Second is a multi-robot workstation designed for testing close-range GNC algorithms, spacecraft autonomous rendezvous and capture (AR&C) technologies, contact dynamics, and assistive sensor systems for autonomous and teleoperated procedures. This workstation consists of five robotic manipulators that may be equipped with satellite mock-ups, advanced end effector systems, and/or GNC sensors. The set-up also contains a high-fidelity satellite mock-up mounted on a motion-based platform that has been modified to include force/torque sensors, thus allowing real-time simulation of satellite contact and grappling dynamics. [View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE, NAVIGATION AND CONTROL

SESSION XII

This session focused on recent experiences in spaceflight GN&C, providing a forum to share insights gained through successes and failures. Discussions include GN&C experiences ranging from Earth orbiters to interplanetary spacecraft. This session is a traditional part of the conference and has shown to be most interesting and informative.

National Chairpersons:

Mimi Aung
NASA Jet Propulsion Laboratory

Chirold Epp
NASA Johnson Space Center

Local Chairpersons:

Kristen Francis
Lockheed Martin
Space Systems Company

Jeff Parker
University of Colorado/Boulder

The following paper numbers were not assigned:

AAS 14-128 to -130

AAS 14-121

RECONSTRUCTED FLIGHT PERFORMANCE OF THE MARS SCIENCE LABORATORY GUIDANCE, NAVIGATION, AND CONTROL SYSTEM FOR ENTRY, DESCENT, AND LANDING

Miguel San Martin,[*] Gavin F. Mendeck,[†] Paul B. Brugarolas,[‡] Gurkirpal Singh[§] and Frederick Serricchio[**]

The Mars Science Laboratory (MSL) project landed successfully the rover *Curiosity* in Gale crater in August 5, 2012, after going through a complex and risky Entry, Descent, and Landing (EDL) sequence that demonstrated a series of innovations and advances in the area of Guidance, Navigation, and Control (GN&C) that resulted in a quantum leap in Mars EDL performance. Among those were the first use at Mars of Entry Guidance to reduce the size of the landing ellipse and the first use of the SkyCrane landing architecture to place a one-ton class rover on the surface of the red planet. Given the first time nature and the associated risks of the new and bold EDL/GN&C design, the project was committed from the start to implement a comprehensive telemetry system for post landing reconstruction of its performance. This paper will give a high level description of the design of the MSL EDL/GN&C system and its performance requirements, the areas of highest uncertainty and risk as understood prior to the arrival to Mars, and its resulting flight performance as reconstructed after landing. [View Full Paper]

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AAS 14-122

EFFECTS OF RADIOISOTOPE THERMOELECTRIC GENERATOR ON DYNAMICS OF THE NEW HORIZONS SPACECRAFT

Gabe D. Rogers,* Sarah H. Flanigan* and Dale Stanbridge†

First in NASA's New Frontiers series of missions, the New Horizons spacecraft was successfully launched towards Pluto on January 19, 2006, conducted a successful flyby of Jupiter on February 28, 2007, and is scheduled to arrive at Pluto on July 14, 2015. In order to operate at up to 50 AU from the Sun the New Horizons spacecraft is powered by a single radioisotope thermoelectric generator (RTG) which generated approximately 209 W of power in August, 2013. As a dual mode spacecraft New Horizons spends long periods of time spinning passively at 5 RPM interspersed with shorter periods of time conducting 3-axis controlled activities. Analysis of spacecraft telemetry following the Jupiter flyby led to the observation of forces and torques acting upon the spacecraft that can be attributed to radiation pressure and thermal re-radiation effects from the RTG. Periodic monitoring of these forces during spinning operations and torques during 3-axis operations has been conducted. This paper attempts to quantify these. This paper also discusses the observed effects on previous deep space missions that utilized one or more RTGs for comparison. [View Full Paper]

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AAS 14-123

THE PRISMA IRIDES RENDEZVOUS EXPERIMENT

Thomas Karlsson,* Robin Larsson,† Björn Jakobsson† and Per Bodin‡

PRISMA was launched on June 15, 2010 to demonstrate strategies and technologies for formation flying and rendezvous. OHB Sweden is the prime contractor for the project which is funded by the Swedish National Space Board with additional support from DLR, CNES, and DTU.

In April 2013, when both the nominal and extended mission phases were successfully completed, new objectives were assigned to the Mango spacecraft and the Tango spacecraft was shut down permanently. An eighteen month journey was started towards a new, non-cooperative space object to demonstrate rendezvous and inspection within an experiment called IRIDES (Iterative Reduction of Inspection Distance with Embedded Safety). Since the start of IRIDES, the Mango spacecraft has completed a series of optimized orbit maneuvers, involving semi-major, inclination and eccentricity changes that have put the spacecraft on a drift towards the new object. The rendezvous is expected in the second half of 2014 and will demonstrate optical relative navigation technologies and the characterization of the rendezvous object and its motion with the use of the on-board video system. The inspection strategy within IRIDES includes a series of inherently collision free drift maneuvers through the cross-track/radial plane of the rendezvous object, and a successively reduction of the closest relative distance.
[View Full Paper]

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AAS 14-124

BEARING NOISE DETECTION, MODELLING AND MITIGATION MEASURES ON ESA'S X-RAY OBSERVATORY XMM-NEWTON

Marcus G. F. Kirsch,[1] Stephen Airey,[2] Patrick Chapman,[3] Denis Di Filippantonio,[3] Anders Elfving,[2] Thomas Godard,[6] Rob Harris,[4] Rainer Kresken,[5] Alastair McDonald,[5] Jim Martin,[1] Paul McMahon,[3] Mauro Pantaleoni,[6] Frederic Schmidt,[7] René Seiler,[2] Tommy Strandberg,[8] Jeroen Vandersteen,[9] Detlef Webert[7] and Uwe Weissmann[7]

ESA's XMM-Newton space observatory launched in 1999 is the flagship of European X-ray astronomy and the most powerful X-ray telescope ever placed in orbit. Originally designed for a 10 years lifetime it seems possible to operate long into this decade since spacecraft and instruments are performing admirably without major degradation. In 2011 it has been discovered that two of the reaction wheels show non periodic (i.e. spontaneous & erratic) friction torque increase caused by ball bearing misbehaviour, probably some unstable motion of the bearing cage(s), during stable pointing phases of the spacecraft, referred to as "bearing noise", "cage instability" or "caging" within this document. We present an analysis of all four reactions wheels identifying the periods of increased friction and provide an empirical model that describes the statistics of the cage instability as it occurs. The model aims to express the frequency of cage instability occurrence, the duration and its effect on friction torque. The model parameters are identified using in-flight telemetry. In addition we discuss possibilities and attempts to cure, potentially avoid or actively counteract this effect. In the framework of XMM-Newton life extension because of high scientific demand and very high ranking by the ESA advisory structure, various options to reduce the fuel consumption have been investigated. Amongst others the process of updating the on-board software of the Attitude Control Computer to allow operating all four reaction wheels in parallel instead of only running three of them as done previously also offers the most promising possibility to apply measures against the effects of increased bearing noise. We present the implementation and results of the applied methods, describe the increased bearing mitigation measures and report on the outcome of re-lubrication exercises performed on two of the wheels to cure the increased bearing torque irregularities. [View Full Paper]

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8 Airbus DS (Astrium GmbH), Friedrichshafen, Germany.

9 RHEA System BV, Noordwijk, The Netherlands.

AAS 14-125

SUOMI-NPP: RECENT EXPERIENCES

Steven Stem,[*] Meredith Larson[†] and Scott Asbury[‡]

Suomi-NPP, the first in a new generation of NOAA polar-orbiting weather satellites, successfully launched October 28th, 2011. This paper provides an overview of the attitude determination and control subsystem (ADCS) commissioning activities during launch and early operations; including lessons learned concerning sun sensor shading coupled with albedo effects, and a study of the dynamic interaction between torque rods and the solar array. A brief description of the science provided by Suomi-NPP's five instruments, which aid in weather forecasting and climate monitoring, and Suomi-NPP's critical role in predicting the path of Hurricane Sandy is also provided.
[View Full Paper]

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† Senior Engineer, Suomi-NPP ADCS Analyst, Ball Aerospace & Technologies Corp., 1600 Commerce Street, Boulder, Colorado 80301, U.S.A.

‡ Senior Program Manager, Joint Polar Satellite System Spacecraft, Ball Aerospace & Technologies Corp., 1600 Commerce Street, Boulder, Colorado 80301, U.S.A.

AAS 14-126

UNITED LAUNCH ALLIANCE: RECENT EXPERIENCES 2013

John G. Reed* and Brian Lathrop†

This has been a busy year for Guidance Navigation and Control at United Launch Alliance. Not only has this been another banner year for our launch manifest, but there has also been intense activity in the evolution of our systems to meet the challenges ahead. From increasing manifest flexibility, to commercial crew and emergency detection, to subsystem upgrades and support for the Marshall Space Flight Centers SLS/iCSP system it has been a productive year. Many of these experiences have impacts leading to increased reliability, cost reductions and product improvement.

This paper delves into GN&C aspects of these experiences and provides insight into the future plans at ULA. [View Full Paper]

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THE LAST DAYS OF GRAIL

Mark S. Wallace, Ralph B. Roncoli, Brian T. Young and Sara J. Hatch*

The Gravity Recovery and Interior Laboratory (GRAIL) extended mission ended on December 17th, 2012 after both spacecraft impacted the side of a small unnamed lunar "mountain" at approximately 75.6° N latitude, 333.2° E longitude. This end was the culmination of a deliberate choice on the part of the Project to eke out every possible gram of scientific and engineering value from the propellant remaining on board. This paper details the design processes and choices made for the last six weeks of the extended mission, from the initial discussions for the Orientale Campaign in June 2012 and concluding with mission's dramatic end six months later. [View Full Paper]

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POSTER SESSION

SESSION 0

Local Chairpersons: Lisa Hardaway
Ball Aerospace & Technologies Corp.

The following papers were not available for publication:

AAS 14-004
Green Propellant Infusion Mission Program Overview, Amy Brown (Ball) (Poster Only)

AAS 14-005
Recent Work Within the Control Systems Design and Analysis Branch at NASA Marshall Space Flight Center, Eric Gilligan (MSFC) (Poster Only)

AAS 14-006
Experimental Design of a Rigid-flexible Satellite Control System, Luiz Carlos Gadelha de Souza (National Institute for Space Research–INPE-Brazil) (Poster Only)

AAS 14-007
Airborne Star Tracker Dynamic Simulator, John Mastrangelo (Ball) (Poster Only)

AAS 14-008
The Minimum Fuel Guidance and Control of an Active Debris Removal Small Satellite, Aaron Avery (USU) (Poster Only)

AAS 14-009
Iridium PRIME: The World's First Turnkey Hosted Payloads Solution, David Anhalt (Iridium Communications) (Poster Only)

The following paper numbers were not assigned:

AAS 14-001 and -010

AAS 14-002

UNIFIED SIMULATION AND ANALYSIS FRAMEWORK FOR DEEP SPACE NAVIGATION DESIGN

Evan J. Anzalone*

Due to the complex nature of deep space navigation, design, analysis, and validation heavily rely on software tools. These are used to support all phases of design from initial phase A-type studies up to flight validation and post-flight analysis. These tools are typically problem- and method-dependent. In order to allow for a common simulation environment for navigation analysis and design, this paper presents a unified framework developed using Model-Based Systems Engineering techniques to describe the notional navigation problem, as well as the analytical framework and its implementation. The functions, processes, and composition of the navigation system and the analysis framework are described using the Systems Model Language (SysML). The utilization of SysML and Model-Based Systems Engineering enables the designer to capture the requirements of the navigation system as well as its implementation and analysis. This model development feeds directly into the development of analytical elements and provides for ease of implementation as well as application to additional navigation problems. This paper describes the development and implementation of a unified simulation and analysis framework for deep space navigation design. [View Full Paper]

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AAS 14-003

SPACECRAFT AND GN&C DEVELOPMENT IN A MODEL-BASED SYSTEMS ENGINEERING ENVIRONMENT*

Christine Edwards-Stewart†

The future of systems engineering for complex space systems development could be revolutionized by the creation of a Model-Based Enterprise (MBE). An MBE is a collaborative environment that integrates activities, tools, models, processes, people, and data. This document discusses the results of a Lockheed Martin pathfinder project for advancing model-based systems engineering (MBSE) capabilities that would support an MBE environment and improve the aerospace industry's systems engineering processes. A guidance, navigation, and control (GN&C) problem was solved in the prototype MBE environment as a use case. The resulting demonstrations showed requirements traceability in a more complete and robust manner, an integrated modeling environment that brings design closure faster and identifies problems earlier, and an impact analysis for a GN&C design change that takes less time and is more thorough than traditional methods. Also, a "virtual build" of the spacecraft was implemented using the modeling environment to identify production inefficiencies. With these results, implementation of these MBE capabilities enables team collaboration and improves affordability through better up-front engineering that reduces downstream errors and the resulting change traffic. [View Full Paper]

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TECHNICAL EXHIBITS

SESSION II

The Technical Exhibits Session was a unique opportunity to observe displays and demonstrations of state-of-the-art hardware, design and analysis tools, and services applicable to advancement of guidance, navigation, and control technology. The latest commercial tools for GN&C simulations, analysis, and graphical displays were demonstrated in a hands-on, interactive environment, including lessons learned and undocumented features. Associated papers, not presented in other sessions, were also provided and could be discussed with the author. Attendees and family members were able to interact with the technical representatives and authors in a social setting.

Local Chairpersons:

Meredith Larson
Ball Aerospace & Technologies Corp.

Rick Jackson
Lockheed Martin (retired)

Most of the Technical Exhibits did not consist of formal written text, and therefore most of the papers for this session were not available for publication. The following papers and paper numbers were not available for publication, or were not assigned:

AAS 14-022 to -030

TECHNICAL EXHIBITS PARTICIPANTS

Airbus Defence and Space
Analytical Graphics, Inc.
Ball Aerospace & Technologies, Corp.
BEI Precision Systems & Space Company, Inc.
Blue Canyon Technologies
Cayuga Astronautics
dSPACE Inc.
Jena-Optronik GmbH
Left Hand Design Corp.
Lockheed Martin Space Systems Company
Monarch High School
NASA Marshall Spaceflight Center
SELEX ES
Sierra Nevada Corporation
SODERN
Surrey Satellite Technology
Texas A&M University
United Launch Alliance, LLC
University of Colorado / Boulder
Utah State University Space Dynamics Lab

AAS 14-021

LASR_CV: VISION-BASED RELATIVE NAVIGATION AND PROXIMITY OPERATIONS PIPELINE

Brent Macomber,[*] Dylan Conway,[*] Kurt A. Cavalieri,[*] Clark Moody[*] and John L. Junkins[†]

To solve the Simultaneous Localization and Mapping (SLAM) problem is to calculate one's own six degree-of-freedom motion with respect to an unknown scene, and to simultaneously generate a three-dimensional map of the scene. This paper presents LASR_CV, a computational vision pipeline for solving the SLAM problem in real time, created by the Land, Air, and Space Robotics (LASR) Lab at Texas A&M University. A modular and extensible framework, LASR_CV is designed for rapid-prototyping of algorithms and sensors for estimation and computer vision. LASR_CV consists of several modules operating in parallel to generate frame-rate pose estimates and geometric models. This modular architecture decouples research topics of interest from the SLAM problem as a whole, enabling developers and researchers to test their software or hardware easily. Each module has "hooks" into the internal data to enable algorithmic tuning or report generation. When combined with inertial measurements, detailed error studies of individual sensors or algorithms can be performed. In this paper, LASR_CV is applied to a laboratory-scale version of an asteroid approach and survey mission. Relative measurements are provided by a Microsoft Kinect active stereo sensor, and the SLAM problem is solved for a general rotating and translating motion, the end result being a high-fidelity three-dimensional reconstruction of a mock asteroid and the relative position and orientation of the mock spacecraft. [View Full Paper]

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