# ASTRODYNAMICS 2020

**Front Cover Image:**

Artemis I, formerly Exploration Mission-1, will be the first integrated test of NASA's deep space exploration systems: the Orion spacecraft, Space Launch System (SLS) rocket and the ground systems at Kennedy Space Center in Cape Canaveral, Florida. The first in a series of increasingly complex missions, Artemis I will be an uncrewed flight test that will provide a foundation for human deep space exploration, and demonstrate our commitment and capability to extend human existence to the Moon and beyond. Credit: NASA photo.

# ASTRODYNAMICS 2020

## Volume 175

## ADVANCES IN THE ASTRONAUTICAL SCIENCES

**Edited by**
**Roby S. Wilson**
**Jinjun Shan**
**Kathleen C. Howell**
**Felix R. Hoots**

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# FOREWORD

This volume is the next in a sequence of AAS/AIAA Astrodynamics Specialist Conference volumes which are published as a part of *Advances in the Astronautical Sciences*. Several other sequences or subseries have been established in this series. Among them are: Spaceflight Mechanics (published for the AAS annually, but recently changed to every second odd number year), Guidance and Control (annual), International Space Conferences of Pacific-basin Societies (ISCOPS, formerly PISSTA), and AAS Annual Conference proceedings. Proceedings volumes for earlier conferences are still available either in hard copy, digital, or in microfiche form. The appendix of the volume lists proceedings available through the American Astronautical Society.

*Astrodynamics 2020*, Volume 175, Advances in the Astronautical Sciences, consists of five parts totaling about 5,400 pages, plus a CD ROM/digital format version which also contains all the available papers.

In our proceedings volumes the technical accuracy and editorial quality are essentially the responsibility of the authors. The session chairs and our editors do not review all papers in detail; however, format and layout are improved when necessary by the publisher.

We commend the general chairs, technical chairs, session chairs and the other participants for their role in making the conference such a success. We would also like to thank those who assisted in organizational planning, registration and numerous other functions required for a successful conference.

The current proceedings are valuable to keep specialists abreast of the state of the art; however, even older volumes contain some articles that have become classics and all volumes have archival value. This current material should be a boon to aerospace specialists.

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**Robert H. Jacobs, Series Editor**

# PREFACE

The 2020 Astrodynamics Specialist Conference was held virtually from August 9th to 13th 2020. Originally the conference was planned to be held at Lake Tahoe, but the unprecedented global COVID-19 pandemic forced significant changes to the conference format. This included for the first time requiring a pre-recorded presentation for each paper in every session to go along with the manuscript and presentation material. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Technical Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Despite the virtual nature of the conference, a record 428 people registered for the meeting. This included 225 students, as well as professional engineers, scientists, and mathematicians representing the government, industry, and academic sectors of the United States and 23 other countries. There were 304 papers presented in 26 sessions on topics spanning the breadth of current research in astrodynamics and space-flight mechanics.

A Special Session devoted to the Artemis Program was held on Tuesday afternoon. The session was co-chaired by Dr. Powtache Valerino from Marshall Space Flight Center and Dr. Paul Thompson from the Jet Propulsion Laboratory. The session was focused on providing a broad overview of the Artemis Program and details of NASA's planned return to the Moon. The session was well attended with average viewership in excess of 70 people throughout the afternoon. We very much appreciate the efforts that Dr. Valerino and Dr. Thompson put into making this session a success.

At the close of the conference on Wednesday evening, the Brouwer Award Lecture was given by Dr. Robert Melton, the 2020 AAS Dirk Brouwer Award Honoree. Dr. Melton is Professor of Aerospace Engineering at The Pennsylvania State University. His research interests include astrodynamics, trajectory optimization and attitude dynamics and control. He is a Fellow of AAS, an Associate Fellow of AIAA, and a Corresponding Member of the International Academy of Astronautics. He has served as Vice President-Technical and Vice President-Publications of AAS, and is a past chair of the Space Flight Mechanics Committee. His lecture was entitled "Two Problems: Rotation and Translation" detailing two missions that serve nicely as examples of the analytical and practical challenges in the dynamics and control of spaceflight.

The editors would like extend their sincerest gratitude to each of the Session Chairs that helped make this meeting a success. The novel virtual sessions were superbly conducted without any issues, due in large part to the experience and dedication that session chairs bring to these conferences year after year. Lastly, we would like to thank the authors for their efforts in performing world-class research and their dedication to present their work to our astrodynamics community, especially in light of all that has transpired during the time leading up to the conference. We are all richer for your service and commitment to excellence.

**Dr. Roby S. Wilson**
**AAS Technical Chair**

**Dr. Kathleen C. Howell**
**AAS General Chair**

**Dr. Jinjun Shan**
**AIAA Technical Chair**

**Dr. Felix R. Hoots**
**AIAA General Chair**

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# ARTIFICIAL INTELLIGENCE AND ITS APPLICATIONS

**AAS 20-425**

# AUTONOMOUS SIX-DEGREE-OF-FREEDOM SPACECRAFT DOCKING MANEUVERS VIA REINFORCEMENT LEARNING

**Charles E. Oestreich,[*] Richard Linares,[†] and Ravi Gondhalekar[‡]**

A policy for six-degree-of-freedom docking maneuvers is developed through reinforcement learning and implemented as a feedback control law. Reinforcement learning provides a potential framework for robust, autonomous maneuvers in uncertain environments with low on-board computational cost. Specifically, proximal policy optimization is used to produce a docking policy that is valid over a portion of the six-degree-of-freedom state-space while striving to minimize performance and control costs. Experiments using the simulated Apollo transposition and docking maneuver exhibit the policy's capabilities and provide a comparison with standard optimal control techniques. Furthermore, specific challenges and work-arounds, as well as a discussion on the benefits and disadvantages of reinforcement learning for docking policies, are discussed to facilitate future research. As such, this work will serve as a foundation for further investigation of learning-based control laws for spacecraft proximity operations in uncertain environments.

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[*] Graduate Student, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 125 Massachusetts Ave, Cambridge, MA 02139, USA.
[†] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 125 Massachusetts Ave, Cambridge, MA 02139, USA.
[‡] Senior Member of the Technical Staff, Guidance & Control Group, The Charles Stark Draper Laboratory, Inc., 555 Technology Square, Cambridge, MA 02139, USA.

**AAS 20-453**

# USING REINFORCEMENT LEARNING TO DESIGN MISSED THRUST RESILIENT TRAJECTORIES

**Ari Rubinsztejn,[*] Kyra Bryan,[†] Rohan Sood,[‡] and Frank E. Laipert[§]**

From ion thrusters to solar sails, spacecraft continue to adopt new and more efficient forms of propulsion. As these low-thrust propulsion methods have become more prevalent, new challenges have arisen. Depending on the mission, low-thrust propulsion elements may need to thrust continuously for days/months. During these thrusting periods, external factors, such as a micro-meteoroid impact or a software glitch, may cause the spacecraft to prematurely cease its thrust stage. Half of all deep space missions enter a safe mode where they cannot thrust every four months. These missed thrust events can result in the complete loss of a spacecraft for time-dependent trajectories like planetary rendezvous. This paper demonstrates how neural networks, trained using reinforcement learning, can autonomously correct for missed thrust events during an interplanetary trajectory.

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[*] Ph.D. Student, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL, 35487, USA. E-mail: arubinsztejn@crimson.ua.edu.
[†] Undergraduate, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL, 35487, USA. E-mail: klbryan1@crimson.ua.edu.
[‡] Assistant Professor, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL, 35487, USA. E-mail: rsood@eng.ua.edu.
[§] Mission Design Engineer, Flight Path Control Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA. E-mail: Frank.E.Laipert@jpl.nasa.gov.

AAS 20-455

# A MACHINE LEARNING SOLUTION TO OPTIMAL LANDING SITE SELECTION AND LANDER CONTROL

Omkar S. Mulekar* and Riccardo Bevilacqua†

Previous investigations have shown that Artificial Neural Networks (ANNs) can be trained to drive closed-loop controllers to yield near optimal trajectories. The problem of selecting an optimal landing site near an objective is defined and investigated for a 3 Degree of Freedom point-mass lunar lander. A trajectory optimization software is used to generate optimal state-action pairs to train one ANN for use in an optimal controller. It is also used to generate data to train a site-selecting ANN from lander initial states, surface geometry, and objective position. The ANNs demonstrate a dynamics-based method of selecting an optimal landing site.

**Keywords**: Neural networks, optimal control, lunar lander, landing site selection

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* PhD Student, Mechanical and Aerospace Engineering, University of Florida, 939 Sweetwater Dr., MAE-A 211, Gainesville, FL 32611, USA.

† Associate Professor, Mechanical and Aerospace Engineering, University of Florida, 939 Sweetwater Dr., MAE-A 211, Gainesville, FL 32611, USA.

AAS 20-473

# MONTE CARLO TREE SEARCH WITH VALUE NETWORKS FOR AUTONOMOUS SPACECRAFT OPERATIONS

Adam Herrmann* and Hanspeter Schaub†

On-board spacecraft task scheduling is a requisite capability for the autonomous exploration of challenging operational environments. Task execution time and resource usage are heavily dependent on the dynamics of the system. Typically, solutions to the spacecraft task scheduling problem consider a limited model of the spacecraft tasks and dynamics or require large amounts of computational power, severely limiting on-board planning and scheduling capability. This paper proposes offline, high-fidelity dynamics simulations and Monte Carlo tree search (MCTS) to compute solutions to the Earth-observing satellite scheduling problem, which are then generalized in a state-action value function approximator that can be executed in real-time onboard spacecraft. MCTS and the state-action value function approximator are deployed in a Basilisk Astrodynamics Software Architecture simulation and compared on the basis of reward, downlink utilization, and computational overhead.

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* PhD Student, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Boulder, CO 80309, USA. AIAA Member.
† Glenn L. Murphy Chair of Engineering, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, CO 80309, USA. AAS Fellow, AIAA Fellow.

AAS 20-475

# ADAPTIVE CONTINUOUS CONTROL OF SPACECRAFT ATTITUDE USING DEEP REINFORCEMENT LEARNING

Jacob G. Elkins,* Rohan Sood,† and Clemens Rumpf‡

As modern and future space missions plan to explore diverse bodies across deep space, the ability to conduct successful spacecraft operations under uncertainty becomes increasingly apparent. A highly accurate and precise spacecraft attitude controller that is robust to the perturbation forces encountered in an uncertain dynamics environment is critical to the ongoing success of spaceflight in deep space. In this work, we present a framework for deriving an adaptive spacecraft attitude controller using deep reinforcement learning. The controller developed is shown to effectively perform large-angle slew maneuvers at industry-standard pointing accuracies. We find that the controller is capable of adapting in the presence of various disturbance torques unseen during training and is system-agnostic of the spacecraft being controlled, even when trained on one spacecraft configuration. Additionally, this study discusses the application specifics that yielded the reported results and discusses possible routes of expansion for future work.

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* Graduate Student, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL 35487, USA. E-mail: jgelkins@crimson.ua.edu.
† Assistant Professor, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL 35487, USA. E-mail: rsood@eng.ua.edu.
‡ Aerospace Engineer, Science and Technology Corporation, NASA Ames Research Center, MS 258-6, Moffett Field, CA 94035, USA. E-mail: clemens.rumpf@nasa.gov.

AAS 20-522

# SAFE LUNAR LANDING VIA IMAGES: A REINFORCEMENT META-LEARNING APPLICATION TO AUTONOMOUS HAZARD AVOIDANCE AND LANDING

**Andrea Scorsoglio,[*] Andrea D'Ambrosio,[†] Luca Ghilardi,[‡] Roberto Furfaro,[§] Brian Gaudet,[**] Richard Linares,[††] and Fabio Curti[‡‡]**

Future missions to the Moon and Mars will require advanced Guidance, Navigation, and Control (GNC) algorithms for the powered descent phase. GNC tasks are generally performed by independent modules. In this paper, reinforcement meta-learning and hazard detection and avoidance are embedded into a single system to derive the optimal thrust command for a safe lunar pinpoint landing using sequences of images and radar altimeter data as inputs. In particular, we incorporate an image-based autonomous hazard detection and avoidance algorithm with real-time GNC for a successful landing. The former is achieved using a machine learning model trained in a supervised fashion to recognize hazardous areas in the camera field of view and selecting a safe point accordingly. Then, within the reinforcement meta-learning framework, this information is used by the agent to learn how to behave in this simulated environment and land safely.

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[*] Ph.D. Student, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, AZ 85721, USA.
[†] Ph.D. Candidate, School of Aerospace Engineering, Sapienza University of Rome, Via Salaria 851, 00138 Rome, Italy.
[‡] Ph.D. Student, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, AZ 85721, USA.
[§] Professor, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, AZ 85721, USA.
[**] Researcher, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, AZ 85721, USA.
[††] Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA.
[‡‡] Professor, School of Aerospace Engineering, Sapienza University of Rome, Via Salaria 851, 00138 Rome, Italy.

**AAS 20-583**

# DEEP REINFORCEMENT LEARNING FOR SAFE LANDING SITE SELECTION WITH CONCURRENT CONSIDERATION OF DIVERT MANEUVERS

**Keidai Iiyama,[*] Kento Tomita,[†] Bhavi A. Jagatia,[‡] Tatsuwaki Nakagawa,[§] and Koki Ho[**]**

This research proposes a new integrated framework for identifying safe landing locations and planning in-flight divert maneuvers. The state-of-the-art algorithms for landing zone selection utilize local terrain features such as slopes and roughness to judge the safety and priority of the landing point. However, when there are additional chances of observation and diverting in the future, these algorithms are not able to evaluate the safety of the decision itself to target the selected landing point considering the overall descent trajectory. In response to this challenge, we propose a reinforcement learning framework that optimizes a landing site selection strategy concurrently with a guidance and control strategy to the target landing site. The trained agent could evaluate and select landing sites with explicit consideration of the terrain features, quality of future observations, and control to achieve a safe and efficient landing trajectory at a system-level. The proposed framework was able to achieve 94.8% of successful landing in highly challenging landing sites where over 80% of the area around the initial target lading point is hazardous, by effectively updating the target landing site and feedback control gain during descent.

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[*] Master Student, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan.
[†] Ph.D. Student, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA.
[‡] Master Student, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA.
[§] Bachelor Student, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA.
[**] Assistant Professor, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA.

**AAS 20-611**

# LOW-THRUST TRAJECTORY DESIGN USING STATE-DEPENDENT CLOSED-LOOP CONTROL LAWS AND REINFORCEMENT LEARNING

**Harry Holt,* Roberto Armellin,† Nicola Baresi,‡ Andrea Scorsoglio,§ and Roberto Furfaro****

Closed-loop feedback-driven control laws can be used to solve low-thrust many-revolution trajectory design and guidance problems with minimal computational cost. They treat the problem from a targeting perspective and hence value stability over optimality. The optimality can be increased by making the parameters state-dependent at the cost of reduced stability. In this paper, an actor-critic reinforcement learning framework is used to make the parameters of the Lyapunov-based Q-law state-dependent. A single-layer neural network ensures the Jacobian of these state-dependent parameters can be calculated and used to enforce stability throughout the transfer. The current results focus on GTO-GEO and LEO-GEO transfers in Keplerian dynamics. A trade-off between optimality and stability is observed for the first, but the added stability increases optimality for the later. Robustness to uncertainties in position and velocity are also investigated, along with the effects of eclipses and dynamical perturbations such as J2, Sun and Moon third body attractions.

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* PhD Student, Surrey Space Centre, University of Surrey, GU2 7XH, Guildford, United Kingdom.
† Professor, Department of Aerospace Vehicles Design and Control, Institut Supérieur de L'Aéronautique et de l'Espace, 31055, Toulouse, France.
‡ Lecturer, Surrey Space Centre, University of Surrey, GU2 7XH, Guildford, United Kingdom.
§ PhD Student, Department of Systems and Industrial Engineering, University of Arizona, Tucson, AZ 85721, USA.
** Professor, Department of Systems and Industrial Engineering, University of Arizona, Tucson, AZ 85721, USA.

AAS 20-616

# REINFORCEMENT LEARNING FOR LOW-THRUST TRAJECTORY DESIGN OF INTERPLANETARY MISSIONS

**Alessandro Zavoli*** **and Lorenzo Federici†**

This paper investigates the use of Reinforcement Learning for the robust design of low-thrust interplanetary trajectories in presence of severe disturbances, modeled alternatively as Gaussian additive process noise, observation noise, control actuation errors on thrust magnitude and direction, and possibly multiple missed thrust events. The optimal control problem is recast as a time-discrete Markov Decision Process to comply with the standard formulation of reinforcement learning. An open-source implementation of the state-of-the-art algorithm Proximal Policy Optimization is adopted to carry out the training process of a deep neural network, used to map the spacecraft (observed) states to the optimal control policy. The resulting Guidance and Control Network provides both a robust nominal trajectory and the associated closed-loop guidance law. Numerical results are presented for a typical Earth-Mars mission. First, in order to validate the proposed approach, the solution found in a (deterministic) unperturbed scenario is compared with the optimal one provided by an indirect technique. Then, the robustness and optimality of the obtained closed-loop guidance laws is assessed by means of Monte Carlo campaigns performed in the considered uncertain scenarios. These preliminary results open up new horizons for the use of reinforcement learning in the robust design of interplanetary missions.

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* Researcher, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, via Eudossiana 18, 00184, Rome, Italy.
† PhD Student, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, via Eudossiana 18, 00184, Rome, Italy.

AAS 20-689

# USING MULTI-OBJECTIVE DEEP REINFORCEMENT LEARNING TO UNCOVER A PARETO FRONT IN MULTI-BODY TRAJECTORY DESIGN

**Christopher J. Sullivan[*] and Natasha Bosanac[†]**

A multi-objective deep reinforcement learning algorithm, designated Multi-Reward Proximal Policy Optimization (MRPPO), is introduced to simultaneously train multiple policies, each with distinct reward functions. In this paper, MRPPO is used to uncover the Pareto front in a multi-objective optimization problem: designing a transfer for a low-thrust-enabled small satellite between two $L_2$ southern halo orbits in the Earth-Moon Circular Restricted Three-Body Problem (CR3BP). Once the policies are trained on this scenario, they are evaluated on a shared set of perturbed initial conditions to facilitate comparisons between policies and explore the time-of-flight and propellant mass usage trade space. A hyperparameter selection exploration is also performed to determine the influence of MRPPO's hyperparameters on the resulting behavior of the policies.

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[*] Ph.D. Student, Colorado Center for Astrodynamics Research, University of Colorado Boulder, CO 80303, USA.
[†] Assistant Professor, Colorado Center for Astrodynamics Research, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, CO 80303, USA.

AAS 20-751

# FORMATION KEEPING FOR SMALLSAT SWARMS USING REINFORCEMENT LEARNING

**Francisco Mendoza,* Patrick Doran,† and Navid Nakhjiri‡**

This paper studies the use of Reinforcement Learning (RL) for satellite swarm formation control. Combinations of two RL algorithms and Artificial Neural Networks (ANN) are considered to find the best performing controller. The RL algorithms under consideration were Deep Q-Network and Deep Deterministic Policy Gradient. The ANN considered is the Feedforward Neural Network. The results pave the foundation for further expansion in the reward function development of more complex spacecraft swarm configurations. It also demonstrates how effective RL algorithms can be used to reliably control a satellite swarm under four different initial swarm states.

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* Graduate Student, Aerospace Engineering, Cal Poly Pomona, 3801 W. Temple Ave., Pomona, CA 91768, USA.
† Graduate Student, Aerospace Engineering, Cal Poly Pomona, 3801 W. Temple Ave., Pomona, CA 91768, USA.
‡ Associate Professor, Aerospace Engineering, Cal Poly Pomona, 3801 W. Temple Ave., Pomona, CA 91768, USA.

# DEEP REINFORCEMENT LEARNING TO ENHANCE FLY-AROUND GUIDANCE FOR UNCOOPERATIVE SPACE OBJECTS SMART IMAGING

**Andrea Brandonisio,[*] Michéle Lavagna,[†] and Davide Guzzetti[‡]**

Driven by several potential applications, leading space agencies are increasingly investing in the gradual automation of space missions. Autonomous flight operations may be a key enabler for on-orbit servicing, assembly and manufacturing (OSAM) missions, carrying inherent benefits such as cost and risk reduction. Within the spectrum of proximity operations, this work focuses on autonomous path-planning for the reconstruction of geometry properties of an uncooperative target. The autonomous navigation problem is called active Simultaneous Localization and Mapping (SLAM) problem, and it has been largely studied within the field of robotics. Active SLAM problem may be formulated as a Partially Observable Markov Decision Process (POMDP). Previous works in astrodynamics have demonstrated that is possible to use Reinforcement Learning (RL) techniques to teach an agent that is moving along a pre-determined orbit when to collect measurements to optimize a given mapping goal. In this work, different RL methods are explored to develop an artificial intelligence agent capable of planning suboptimal paths for autonomous shape reconstruction of an unknown and uncooperative object via imaging. Proximity orbit dynamics are linearized and include orbit eccentricity. The geometry of the target object is rendered by a polyhedron shaped with a triangular mesh. Artificial intelligent agents are created using both the Deep Q-Network (DQN) and the Advantage Actor Critic (A2C) method. State-action value functions are approximated using Artificial Neural Networks (ANN) and trained according to RL principles. Training of the RL agent architecture occurs under fixed or random initial environment conditions. A large database of training tests has been collected. Trained agents show promising performance in achieving extended coverage of the target. Policy learning is demonstrated by displaying that RL agents, at minimum, have higher mapping performance than agents that behave randomly. Furthermore, RL agent may learn to maneuver the spacecraft to control target lighting conditions as a function of the Sun location. This work, therefore, preliminary demonstrates the applicability of RL to autonomous imaging of an uncooperative space object, thus setting a baseline for future works.

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[*] Graduate Student, Aerospace Department, Politecnico di Milano, Italy. E-mail: andrea.brandonisio@mail.polimi.it.
[†] Associate Professor, Aerospace Department, Politecnico di Milano, Italy. E-mail: michelle.lavagna@polimi.it.
[‡] Assistant Professor, Aerospace Department, Auburn University, AL 36849, USA. E-mail: guzzetti@auburn.edu.

AAS 20-757

# A MACHINE LEARNING APPROACH FOR ENABLING MISSION PLANNING OF TIME-OPTIMAL ATTITUDE MANEUVERS

**Reed Ransom Smith,[*] Mark Karpenko,[†] and Brian M. Wade[‡]**

Time-optimal spacecraft rotations have been developed and implemented on orbiting spacecraft, highlighting opportunities for improving slew performance. Double-digit reductions in the time required to slew from one attitude to another have been demonstrated. However, the ability to perform mission planning to make use of minimum time slewing maneuvers is largely precluded by the time needed to compute minimum time maneuver profiles. Machine learning approaches can eliminate the need to generate problem solutions by approximating time-optimal maneuver times with sufficient accuracy for planning, using only the initial and final attitude requirements. We outline the advantages of time-optimal spacecraft maneuvers, a planning construct for evaluating legacy and machine learning maneuver time generators, and the machine learning processes that enable this approach.

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[*] Graduate Student, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, 1 University Cir., Monterey, CA 93943, USA.
[†] Research Associate Professor, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, 1 University Cir., Monterey, CA 93943, USA.
[‡] Director, The Research and Analysis Center – Monterey (TRAC-MTRY), 700 Dyer Road, Monterey, CA 93943, USA.

# ATTITUDE DYNAMICS, DETERMINATION AND CONTROL

**AAS 20-400**

# SPACECRAFT ATTITUDE CONTROL ON *SO*(3) BASED ON KOOPMAN OPERATOR

**Ti Chen* and Jinjun Shan†**

This paper proposed an attitude control approach on the basis of Koopman operator theory. The rotation matrix is used to describe the spacecraft attitude. For the spacecraft with slow angular velocity, a reduced linear system is built to approximate the original nonlinear attitude dynamics on $SO(3)$ based on a set of measurement functions. Then, LQR technique is adopted to develop an attitude controller. Finally, the effectiveness of the proposed attitude controller design method is verified via some numerical examples.

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* Post-Doctoral Fellow, Department of Earth and Space Science and Engineering, York University, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada.
† Professor, Department of Earth and Space Science and Engineering, York University, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada.

AAS 20-470

# AVERAGED SOLAR TORQUE ROTATIONAL DYNAMICS FOR DEFUNCT SATELLITES[*]

Conor J. Benson[†] and Daniel J. Scheeres[†]

Spin state predictions for defunct geosynchronous (GEO) satellites are valuable for active debris removal and servicing missions as well as material shedding studies and attitude-dependent solar radiation pressure (SRP) modeling. Previous studies have shown that solar radiation torques can explain the observed spin state evolution of some GEO objects via the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect. These studies have focused primarily on uniform rotation. Nevertheless, many objects are in non-principal axis rotation (i.e. tumbling). Recent exploration of the tumbling regime for the family of retired GOES 8-12 satellites has shown intriguing YORP-driven behavior including spin-orbit coupling, tumbling cycles, and tumbling period resonances. To better explore and understand the tumbling regime, we develop a semi-analytical tumbling-averaged rotational dynamics model. The derivation requires analytically averaging over the satellite's torque-free rotation, defined by Jacobi elliptic functions. The averaged model is found to capture the general long-term behavior of the full dynamics while reducing computation time by several orders of magnitude. The tumbling averaged model also helps explain the observed behavior and promises to facilitate exploration of general long-term rotational dynamics for defunct satellites and rocket bodies.

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[*] An expanded version of this paper was submitted for review in the *Journal of Guidance, Control, and Dynamics*.

[†] Department of Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Drive, Boulder, CO 80303, United States.

**AAS 20-477**

# STABILITY AND STEADY STATE ERROR ANALYSIS FOR SATELLITE MAGNETIC ATTITUDE REGULATION

**Mohammed A. A. Desouky* and Ossama Abdelkhalik†**

In magnetic attitude maneuvers, magnetic rods and magnetometers usually operate alternatively, to avoid the high noise on magnetometers due to magnetic rods currents. As a result, magnetic rods operate on a duty cycle basis. Most studies neglect the impact of the duty cycle in the stability and steady state error analyses. It is shown in this paper that this duty cycle does impact the stability and the steady state error in attitude regulation maneuvers. In addition, this duty cycle causes an increase in the maneuver time and the power consumption, compared to that computed by neglecting the duty cycle effect. For detumbling maneuvers, however, it is shown that asymptomatic stability can been proved. Simulation results confirm the obtained analytical results.

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* PhD, Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, MI 49931, USA. E-mail: madesouk@mtu.edu.
† Associate Professor, Department of Aerospace Engineering, Iowa State University, Ames, IA, 50011, USA.
E-mail: ossama@iastate.edu.

**AAS 20-478**

# PROPELLANT-FREE ATTITUDE-TRAJECTORY CONTROL OF SOLAR SAILS WITH VARIABLE-SHAPE MECHANISM

**Toshihiro Chujo***

Capability to vary the shape of spacecraft is an innovative system as it realizes multiple functions variable on orbit. In particular, it enables solar sails to realize propellant-free attitude-trajectory concurrent control by moving the sails to change solar radiation pressure (SRP) and its torque. We systemized the dynamics of the attitude motion and its control under SRP, and studied its application to trajectory control without propellant consumption.

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* Assistant Professor, Department of Mechanical Engineering, School of Engineering, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro-ku, Tokyo, 152-8550, Japan.

**AAS 20-483**

# SPACECRAFT MOMENT OF INERTIA ESTIMATION VIA RECURRENT NEURAL NETWORKS

**Nathaniel Enders,* Joseph Curro,† Joshuah Hess‡ and Richard Cobb§**

In satellite attitude control, traditional control techniques are only usable when the satellite's mass characteristics are accurately known. However, there are many scenarios where this knowledge may be unknown. For example, it may be difficult to get the mass characteristics of a satellite if it is damaged by micrometeorites or orbital debris, or if the satellite docks with an object of unknown mass. In situations such as these, it may be necessary to use non-traditional estimation techniques before the satellite can be controlled. The following paper investigates the use of artificial neural networks to estimate the inertia matrix of an arbitrary body given a time history of angular velocity. One scenario considers the torque-free motion of a satellite, and two other scenarios consider disturbance and commanded torques. The data was generated in MATLAB and the recurrent neural network (RNN) was constructed and trained in Python. The data sets contain randomly generated inertia matrices and their corresponding angular velocity trajectory and the second data set contains gravity gradient torque and a commanded input torque. Given an input of either only angular velocity or including torques, the RNN predicted the three principal moments of inertia. The truth labels for the RNN were the original principal moments of inertia. In a torque-free environment, the RNN was unable to estimate the moments of inertia, but could estimate the relative moments of inertia. In the presence of torque, where a portion is known, the RNN was able to estimate the moments of inertia with relative success. When the applied torques are unknown to the RNN, the estimation error was larger than when a portion of the applied torque is known. Given more training data, the RNN would likely reduce the estimation error in the presence of torque.

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* Master's Student, Department of Aeronautics & Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

† Assistant Professor, Department of Electrical and Computer Engineering, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

‡ Assistant Professor, Department of Aeronautics & Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

§ Professor, Department of Aeronautics & Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

**AAS 20-501**

# ATTITUDE-INDEPENDENT MAGNETOMETER CALIBRATION FOR SPINNING SPACECRAFT USING QUASI-MEASUREMENTS

**Halil Ersin Soken,* Mustafa Efe Çetin,† and Shin-ichiro Sakai‡**

Magnetometers are essential sensors for attitude estimation in small spacecraft due to their robust, inexpensive and lightweight characteristics. However, their direct usage is not applicable due to sensor errors. These errors limit the overall attitude estimation accuracy. This study proposes a complete real-time attitude-independent magnetometer calibration algorithm for spinning spacecraft. The recursive algorithm aims estimating the complete error state, which consists the magnetometer bias vector, scale factors and non-orthogonality corrections, in real-time, without requiring any attitude information. To build the algorithm the well-known attitude-independent observation that is based on the magnitude of the sensed magnetic field is aided with new introduced quasi-measurements. The algorithm is tested with both simulations and real data from the Arase spacecraft of JAXA. Three quasi-measurements, which are derived using dynamic characteristics of the spacecraft, considerably improve the convergence characteristics of the filter and the estimation accuracy.

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* Dr., Chief Researcher, TÜBITAK Space Technologies Research Institute, Ankara, Turkey.
† Graduate Student, Middle East Technical University, Ankara, Turkey.
‡ Professor, Japan Aerospace Exploration Agency, Japan.

AAS 20-503

# MOTION PLANNING AND CONTROL FOR ON-ORBIT ASSEMBLY USING LQR-RRT* AND NONLINEAR MPC

**Bryce Doerr[*] and Richard Linares[†]**

Deploying large, complex space structures is of great interest to the modern scientific world as it can provide new capabilities in obtaining scientific, communicative, and observational information. However, many theoretical mission designs contain complexities that must be constrained by the requirements of the launch vehicle, such as volume and mass. To mitigate such constraints, the use of on-orbit additive manufacturing and robotic assembly allows for the flexibility of building large complex structures including telescopes, space stations, and communication satellites. The contribution of this work is to develop motion planning and control algorithms using the linear quadratic regulator and rapidly-exploring randomized trees (LQR-RRT*), path smoothing, and tracking the trajectory using a closed-loop nonlinear receding horizon control optimizer for a robotic Astrobee free-flyer. By obtaining controlled trajectories that consider obstacle avoidance and dynamics of the vehicle and manipulator, the free-flyer rapidly considers and plans the construction of space structures. The approach is a natural generalization to repairing, refueling, and re-provisioning space structure components while providing optimal collision-free trajectories during operation.

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[*] Postdoctoral Fellow, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
[†] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

# EVALUATION OF VIBRATION TRANSFER CHARACTERISTICS IN MICRO VIBRATION DISTURBANCE SUPPRESSION MECHANISM USING SUPERCONDUCTING FLUX PINNING EFFECT

**Shogo Tochimoto,[*] Takuma Shibata,[†] and Shinichiro Sakai[‡]**

In recent years, the image resolution required for space telescopes has dramatically increased. It is necessary to prevent vibration and heat from transferring to observation equipment. To achieve the requirement, we have been proposing a mechanism that separates mission and bus parts to suppress vibration and heat propagation. In the previous research, the proposed mechanism has been analyzed by simulation. In this paper, we conduct an experiment to apply a small vibration disturbance to the connecting part by magnetic flux pinning, and the effectiveness of the analysis method was verified by comparing the measured vibration transfer characteristics with the analysis results. As a result of the comparison, the relative error between the analysis and the measurement was more than 10%, and it was found that the estimation was sufficient.

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[*] Graduate School of Frontier Sciences, The University of Tokyo, Japan, Master 2nd grade.
[†] Canon Electronics Co., Ltd., Japan.
[‡] Japan Aerospace Exploration Agency / JAXA, Japan, Professor.

AAS 20-529

# FUNDAMENTAL ANALYSIS ON ATTITUDE AND BODY CONFIGURATION SIMULTANEOUS CONTROL FOR A MULTI RIGID BODY SPACECRAFT

**Yuki Kubo[*] and Junichiro Kawaguchi[†]**

In this research, a fundamental analysis is given on an attitude and body configuration simultaneous control for a multi rigid body spacecraft and especially we focus on a maneuver referred to as 4-stroke flip flop (4-FF) maneuver. An exclusive difficulty in this problem lies in its strong nonlinearity, high-dimensionality and underactuation. The author formulated a polynomial approximate solution of attitude motion, where Jacobian and Hessian tensors are derived in an explicit analytical form. Moreover, this polynomial approximation provides an approximate global distribution of 4-FF maneuver. Compared to a usual numerical integration, the proposed method has much less computational cost and it serves as a key tool to solve highly complicated motion planning problem of an attitude and body configuration simultaneous control.

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[*] Ph.D. Candidate, Department of Aeronautics and Astronautics, the University of Tokyo, 1-1, 3 Cho-me, Yoshinodai, Chuo-ku, Sagamihara City, Kanagawa, 252-5210, Japan.

[†] Professor, Department of Space Flight Systems, ISAS/JAXA, 1-1, 3 Cho-me, Yoshinodai, Chuo-ku, Sagamihara City, Kanagawa, 252-5210, Japan.

**AAS 20-533**

# A MULTIRATE VARIATIONAL APPROACH TO SIMULATION AND OPTIMAL CONTROL FOR FLEXIBLE SPACECRAFT

**Yana Lishkova,[*] Sina Ober-Blöbaum,[†]
Mark Cannon,[‡] and Sigrid Leyendecker[§]**

We propose an optimal control method for simultaneous slewing and vibration control of flexible spacecraft. Considering dynamics on different time scales, the optimal control problem is discretized on micro and macro time grids using a multirate variational approach. The description of the system and the necessary optimality conditions are derived through the discrete Lagrange-d'Alembert principle. The discrete problem retains the conservation properties of the continuous model and achieves high fidelity simulation at a reduced computational cost. Simulation results for a single-axis rotational maneuver demonstrate vibration suppression and achieve the same accuracy as the single rate method at reduced computational cost.

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[*] DPhil Student, Department of Engineering Science, University of Oxford, Parks Road, OX1 3PJ Oxford, UK.
[†] Professor, Department of Mathematics, University of Paderborn, Warburger Str. 100, D-33098 Paderborn, Germany.
[‡] Associate Professor, Department of Engineering Science, University of Oxford, Parks Road, OX1 3PJ Oxford, UK.
[§] Prof., Chair of Applied Dynamics, University of Erlangen-Nuremberg, Immerwahrstrasse 1, D-91058 Erlangen, Germany.

AAS 20-534

# ESTIMATION OF ATTITUDE DYNAMICS PARAMETERS FOR AN EARTH-IMAGING SATELLITE CONSIDERING THE DESIGN LIMITATIONS

**Semsettin Numan Sozen,* Murat Gokce,† Farid Gulmammadov,‡ Halil Ersin Soken,§ and Cagatay Yavuzyilmaz****

Designing an attitude controller for an Earth-imaging satellite requires precise knowledge of the satellite's attitude dynamics parameters. This study proposes an extended Kalman filter algorithm for estimating the satellite's inertia terms and the reaction wheel alignment angles. Design limitations for the satellite such as the specific attitude angles to be avoided for safe operation of the camera and star sensors are considered as constraints in the control trajectory. Demonstrations show rapid convergence of the estimation results to the actual values without any violation of the attitude constraints.

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* Researcher, TÜBITAK Space Technologies Research Institute, Ankara, Turkey.
E-mail: numan.sozen@tubitak.gov.tr.
† Dr. Chief Researcher, TÜBITAK Space Technologies Research Institute. E-mail: murat.gokce@tubitak.gov.tr.
‡ Chief Researcher, TÜBITAK Space Technologies Research Institute. E-mail: farid.gulmammadov@tubitak.gov.tr.
§ Dr. Chief Researcher, TÜBITAK Space Technologies Research Institute. E-mail: ersin.soken@tubitak.gov.tr.
** Dr. Chief Researcher, TÜBITAK Space Technologies Research Institute.
E-mail: cagatay.yavuzyilmaz@tubitak.gov.tr.

AAS 20-545

# RECURSIVE STAR-IDENTIFICATION ALGORITHM USING AN ADAPTIVE SVD-BASED ANGULAR VELOCITY ESTIMATOR

**Hunter Johnston,[*] Carl Leake,[†]**
**Marcelino M. de Almeida,[‡] and Daniele Mortari[§]**

This paper describes an algorithm obtained by merging a recursive star identification algorithm with a recently developed adaptive SVD-based estimator of the angular velocity vector (QuateRA). In a recursive algorithm, the more accurate the angular velocity estimate, the quicker and more robust to noise the resultant recursive algorithm is. Hence, combining these two techniques produces an algorithm capable of handling a variety of dynamics scenarios. The speed and robustness of the algorithm are highlighted in a selection of simulated scenarios. First, a speed comparison is made with the state-of-the-art lost-in-space star identification algorithm, Pyramid. This test shows that in the best case the algorithm is on average an order of magnitude faster than Pyramid. Next, the recursive algorithm is validated for a variety of dynamic cases including a ground-based "Stellar Compass" scenario, a satellite in geosynchronous orbit, a satellite during a reorientation maneuver, and a satellite undergoing non-pure-spin dynamics.

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[*] PhD Candidate, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
E-mail: hunterjohnston@tamu.edu.
[†] PhD Candidate, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
E-mail: leakec@tamu.edu.
[‡] University of Texas at Austin, Austin, TX 78712, USA. E-mail: marcelino.malmeidan@utexas.edu.
[§] Professor, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA. IEEE and AAS Fellow.
IAA Corresponding member. E-mail: mortari@tamu.edu.

**AAS 20-548**

# STAR TRACKER BASED INERTIAL STATE ESTIMATION ON PLANETARY BODIES: AN UPDATE ON THE STELLAR POSITIONING SYSTEM

**Anthony Gardner,* Hunter Johnston,† Carl Leake,‡ Evan Anzalone,§ and Daniele Mortari****

In order to conduct future surface operations on the Moon and Mars, NASA will look to autonomous navigation technologies that can fill the infrastructure limitations of the LORAN-C and Global Positioning System: one such system to meet this need is the Stellar Positioning System (SPS). This paper improves on the original SPS algorithm by leveraging recent technological advances that have improved the resolution of gravity models for the Earth, Moon, and Mars. The algorithm improvements developed in this paper takes advantage of the geoid deflections-of-vertical to correct the direction of the measured unit gravity vector. In addition, a state-of-the-art inclination sensor is considered, which could theoretically provide sub-meter position accuracy after applying the geoid correction.

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* Master's Student, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
† PhD Candidate, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
‡ PhD Student, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
§ Aerospace Engineer, EV42, NASA/Marshall Spaceflight Center, Huntsville, AL 35801, USA.
** Professor of Aerospace Engineering, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.

AAS 20-576

# ENCODING OPTIMAL ATTITUDE CONTROL SOLUTIONS WITH LONG-SHORT TERM MEMORY NEURAL NETWORKS

**Vincent M. Audo,* Mark Karpenko,† and Brian M. Wade‡**

Continuous-time trajectory optimization can be used to find shortest-time slews for point-to-point reorientation maneuvers. Currently, these maneuvers are solved on the ground because spacecraft typically lack the computational resources required to compute minimum-time attitude trajectories as part of their onboard flight software. Compared to a dynamic optimization algorithm, executing the forward pass of a neural network is computationally inexpensive. Moreover, neural networks can encode an enormous amount of information in a small memory footprint. In this paper, we explore the long-short term memory (LSTM) neural network architecture as a means to enable an efficient implementation of minimum-time attitude control. We show that the LSTM can be trained to accurately predict maneuver trajectories for a wide variety of minimum-time point-to-point attitude maneuvers. The trained LSTM can then be used as a logic for instantiating an onboard maneuver generator of a standard quaternion error feedback control system.

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* Graduate Student, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, United States of America.

† Research Associate Professor and corresponding author, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, United States of America. E-mail: mkarpenk@nps.edu.

‡ Director, The Research and Analysis Center, Naval Postgraduate School, Monterey, CA 93943, United States of America.

**AAS 20-598**

# MACHINE LEARNING ENHANCED GYRO CALIBRATIONS BASED ON EXTENDED KALMAN FILTER

**Hao Peng*** **and Xiaoli Bai†**

The paper proposes a novel machine learning (ML) gyro calibration method that can achieve higher accuracy gyro calibration and attitude estimation accuracy than the standard extended Kalman filter (EKF) when high-accuracy measurements are only available in a part of the orbital period. The ML calibration method does not make assumptions on the form of the sensor error model but directly learns it from data. Using a simulated torque-free satellite motion, we demonstrate the ML calibration method is effective. The results show that the gyro calibration achieves smaller residual errors compared with using standard EKF. Meanwhile, the attitude accuracy is also improved since less noise is introduced by the gyro measurement. The impact of different simulated gyro error models and the structure of the ML models are also analyzed through a series of experiments.

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* Postdoctoral Associate, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ 08854, USA. E-mail: astro.H.Peng@gmail.com.
† Associate Professor, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ 08854, USA. E-mail: xiaoli.bai@rutgers.edu.

**AAS 20-638**

# FUZZY OPTIMAL VARIANCE CONTROL OF A FLEXIBLE SPACECRAFT SUBJECT TO ACTUATORS AMPLITUDE AND RATE CONSTRAINTS

**Chokri Sendi***

This paper investigates the performance of a fuzzy optimal variance control technique for attitude stability and vibration suppression of a flexible spacecraft made of a rigid platform and multiple flexible appendages. The proposed technique addresses the problem of actuators amplitude and rate constraints. The fuzzy model of the spacecraft is based on the Takagi-Sugeno(T-S) fuzzy model with disturbances and the control law is designed based on the Parallel Distributed Compensation technique (PDC). The problem is cast as an optimization problem in the form of Linear Matrix Inequalities (LMI). The performance and the stability of the proposed controller are examined through numerical simulation.

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* Assistant Professor, Department of Mechanical Engineering, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, Alaska 99508, USA.

**AAS 20-652**

# UNCERTAINTY QUANTIFICATION FOR A BATCH FILTER: ESTIMATING THE ANGULAR VELOCITY OF A RIGID-BODY IN NEAR PURE-SPIN CONDITION

**Siddarth Kaki[*] and Maruthi R. Akella[†]**

The problem of estimating relative pose and angular velocity for uncooperative space objects has garnered great interest, especially within applications such as asteroid mapping and satellite servicing. This work proposes a batch estimator based on relative orientation measurements to estimate not only the angular velocity magnitude and spin-axis direction of the target body, but also the accompanying uncertainty bounds for the resulting spin-axis direction estimate under reasonable assumptions. Instead of a recursive filtering methodology, the batch formulation pursued in this paper is well-suited to exploit the geometric properties associated with singular value decomposition techniques. This batch approach relinquishes the need for an iterative scheme to compute the error bounds upon the estimated spin-axis direction.

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[*] Ph.D. Student, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA. E-mail: siddarthkaki@utexas.edu.

[†] E.P. Schoch Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA. E-mail: makella@mail.utexas.edu. AAS Fellow.

**AAS 20-678**

# ADAPTIVE ATTITUDE TRACKING CONTROL: PRESERVING THE SELF-REDUCTION PROPERTY THROUGH TIME-VARYING FEEDBACK GAINS

**S. P. Arjun Ram[*] and Maruthi R. Akella[†]**

The adaptive control problem for attitude tracking is revisited for rigid spacecraft with inertia uncertainties. A new adaptive controller is designed for this problem, that retains the classical proportional-derivative plus feedforward (PD+) structure, wherein the desired attitude state is represented by quaternions and full-state feedback (attitude and angular rate) is assumed. Unlike the vast majority of prior results available in the literature for this problem, a major feature of the new 'PD+' law is the introduction of time-varying feedback gains along with an adaptive estimate for the inertia matrix, guaranteeing stable asymptotic tracking of the desired reference trajectories. No further restrictions are placed upon the initial conditions, reference trajectories or the requirement for a priori availability of bounds upon the inertia matrix. Saliently, this new control law preserves the self-reduction property, i.e., the controller reduces to simply having the linear PD feedback structure for the special case of set-point regulation with no further dependence upon the inertia matrix. The controller is tested in simulation to study its effectiveness and to compare against existing methods.

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[*] Graduate Research Assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA. E-mail: arjun.ram@utexas.edu.
[†] E.P. Schoch Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA. E-mail: makella@mail.utexas.edu. AIAA Associate Fellow, AAS Fellow.

AAS 20-687

# NONLINEAR AND MINIMUM-TIME MODEL PREDICTIVE CONTROL FOR CUBESATS USED IN A DISTRIBUTED SPACECRAFT SYSTEM

**Alexa Mortenson[*] and Hyeongjun Park[†]**

With the advancement of CubeSat technology and availability, they are being used in more novel missions including distributed space telescopes used for higher resolution imaging. These missions, however, do not come without challenges. Specifically, by placing a distributed telescope mission in Low Earth Orbit (LEO), the shorter orbit times induce a time constraint to conduct an observation to collect images. In order to provide more time for the time-sensitive tasks of perfect alignment in relative position and velocity, the need for a quick settling time of slew maneuvering becomes critical to achieve precise pointing accuracy for mission success in limited time. In this paper, two control methods are designed for a distributed space telescope using CubeSats: (1) nonlinear model predictive control (MPC) and (2) minimum-time MPC. The performance of two controllers are evaluated with respect to settling time while rejecting disturbances encountered in LEO.

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[*] Graduate Student, Department of Mechanical and Aerospace Engineering, New Mexico State University, 1780 E University Ave., Las Cruces, NM 88003, USA.
[†] Assistant Professor, Department of Mechanical and Aerospace Engineering, New Mexico State University, 1780 E University Ave., Las Cruces, NM 88003, USA.

AAS 20-690

# STOCHASTIC SPACECRAFT NAVIGATION AND CONTROL IN LIE GROUP SE(3) AROUND SMALL IRREGULAR BODIES

**Matthew M. Wittal,[*] Gennaro Mangiacapra,[†] Akku Appakonam,[‡] Morad Nazari,[§] and Elisa Capello[**]**

This work presents a novel rigid-body spacecraft navigation and control architecture within the compact special Euclidean group SE(3) and its tangent bundle TSE(3) considering stochastic processes in the system. The formulation developed herein effectively combines the translational and rotational motions of a rigid-body spacecraft into a single compact set and presents the integration of a stochastic estimator-based controller for spacecraft motion in a highly nonlinear, irregular-shaped small-body environment using a novel TSE(3) framework. The theoretical navigation and control architecture created here is studied for the cases of the Saturnian moon Pan and a hovering problem around the asteroid Bennu. The effectiveness of the estimator and controller are examined in the simulations. Furthermore, the augmentation of the stochastic estimator and the almost-globally asymptotically stabilizing controller is proved to be a reliable, functional approach for spacecraft navigation and control in highly perturbed environments near small bodies with irregular shapes.

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[*] Graduate Student, Aerospace Engineering Department, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA & Scientist, NASA Kennedy Space Center, FL 32899, USA.
[†] Graduate Student, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Torino 10129, Italy.
[‡] Graduate Student, Aerospace Engineering Department, Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA.
[§] Assistant Professor, Aerospace Engineering Department, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA.
[**] Assistant Professor, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, CNR-IEIIT, Torino 10129, Italy.

AAS 20-692

# OPTIMAL TRAJECTORY GENERATION FOR MULTI-BODY FLEXIBLE SYSTEMS WITH VIBRATION COMPENSATION VIA PSEUDOSPECTRAL METHODS

**Brian W. Bishop,[*] Richard G. Cobb,[†] and Costantinos Zagaris[‡]**

For a free-floating, flexible, multi-body system, traditional maneuver generation relies on control/velocity constraints artificially imposed to minimize impacts from nonlinear/coupling effects, while employing notch filters to attenuate vibrational response. This paper investigates pseudospectral methods as a means of generating minimum-time trajectories which simultaneously addresses control profile frequency content leading to better suppression of the system's vibrational modes. This technique allows the expansion of the artificially restricted control and velocity envelopes, decreasing maneuver time without negatively impacting the system's vibrational response.

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[*] PhD Candidate, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH 45433, USA.

[†] Professor, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH 45433, USA.

[‡] Assistant Professor, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, 45433, USA.

**AAS 20-701**

# SPACECRAFT ATTITUDE TESTBED

**Alex Cameron Bailey,[*] Ahmad Bani Younes,[†] and Mohammad Ramadan[‡]**

Spacecraft attitude determination and control is a crucial element for mission success. It demands efficient and robust algorithms. This paper develops a small-scale testbed for satellite attitude control and determination systems (ACDS), comprised of four orthogonal spinning rotors on a flat base to simulate a satellite's reaction control systems. The primary purpose of the paper is to perform risk reduction hardware-in-the-loop experiments for spacecraft Guidance, Navigation and Control (GNC) functions; including pointing, sensing, and platform stabilization. Spacecraft attitude testbed (SAT) is a custom 3-DOF experimental attitude platform for testing attitude control and estimation algorithms. Building a low-cost, ground-based test platform to mimic the conditions of a weightless satellite in space. The attitude control authority is applied through torque inputs by on-board reaction wheels imparting stored angular momentum and altering the platforms rotational dynamics. The primary goal of this paper is to design and build a low-cost reaction wheel platform using custom and commercial off-the-shelf (COTS) hardware in order to test state-of-art control algorithms for the attitude control of small satellites type missions. The key contribution of this work enables the applicability of designing novel attitude estimation and control laws. We study various cases, fault detection cases, and investigate efficient resolutions. Preliminary simulation examples are presented to demonstrate the performance of the platform. We aim to expanded this work to solve for more efficient, adaptive, and robust control algorithms based on real time system feedback.

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[*] Research Assistant, Aerospace Engineering, San Diego State University, San Diego, CA, USA.
[†] Assistant Professor, Aerospace Engineering, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182-1308, USA. AIAA Member.
[‡] Research Assistant, Aerospace Engineering, San Diego State University, San Diego, CA, USA.

**AAS 20-705**

# GUIDANCE AND TRACKING CONTROL FOR RIGID BODY ATTITUDE USING TIME-VARYING ARTIFICIAL POTENTIALS

**Abhijit Dongare,[*] Amit K. Sanyal,[†] Hossein Eslamiat[‡] and Sasi Prabhakaran Viswanathan[§]**

This paper presents a guidance and attitude tracking control scheme in continuous time for a rigid body in SO(3), using time-varying artificial potentials. This novel idea leads to generation of an attitude trajectory that passes through desired attitude waypoints and feedback tracking of this trajectory. These waypoints can also be used for avoiding attitude or pointing direction constraints so that safe attitude navigation is ensured. Artificial time-varying potential fields at these waypoints that are attractive, are introduced. Bump functions of time, which are smooth but not real analytic, are used to generate these potentials at the desired attitude waypoints. For the terminal attitude, a different type of smooth function is used. The rigid body attitude in these time-varying potential fields gets attracted towards the desired attitude waypoints during certain time periods. This generates an attitude trajectory passing through these desired waypoints sequentially in time. A Lyapunov analysis is carried out to show stable attitude tracking through the desired waypoints and ending at the terminal attitude, using these time-varying artificial potentials. Numerical simulations are carried out to test the performance of this attitude guidance and tracking scheme.

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[*] Ph.D. Student, Department of Mechanical and Aerospace Engineering, Syracuse University, New York 13244, USA. E-mail: audongar@syr.edu.

[†] Associate Professor, Department of Mechanical and Aerospace Engineering, Syracuse University, New York 13244, USA. E-mail: aksanyal@syr.edu.

[‡] Ph.D. Student, Department of Mechanical and Aerospace Engineering, Syracuse University, New York 13244, USA. E-mail: heslamia@syr.edu.

[§] Akrobotix LLC, Syracuse, New York 13202, USA.

**AAS 20-713**

# A RECURRENT NETWORK FOR INFINITY NORM CONTROL ALLOCATION IN SPACECRAFT ATTITUDE CONTROL

**Benjamin Diehl[*] and Mark Karpenko[†]**

Spacecraft with redundant momentum exchange devices typically utilize a least squares pseudoinverse to map the requested body frame torques to individual reaction wheels. The use of an infinity norm control allocation has the benefits of better utilizing the capability of the reaction wheels. In this paper, a recurrent network is proposed for determining an infinity norm pseudoinverse in a spacecraft attitude control loop. The recurrent network is a dynamic system that solves an optimization problem without iteration when implemented in a Very Large Scale Integrated (VSLI) circuit or Field-Programmable Analog Array (FPAA) and can therefore be used on-board a spacecraft. Comparisons will be made between the conventional least squares approach and the infinity norm approach in terms of target acquisition of an imaging spacecraft.

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[*] Graduate Student, 591 Curriculum, Naval Postgraduate School, Monterey, CA 93943, USA.
[†] Research Associate Professor and corresponding author, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, USA.

AAS 20-716

# POINTING SYSTEM DESIGN FOR THE CORONAL DIAGNOSTIC EXPERIMENT (CODEX) USING A MODIFIED STATE OBSERVER AND A NEURAL NETWORK CONTROLLER

**Pavel Galchenko,* Henry Pernicka,† and S. N. Balakrishnan‡**

The COronal Diagnostic Experiment mission requires precision attitude pointing and stability in the arcsecond range to study coronal mass ejections from the Sun. While the Wallops Arc Second Pointer platform successfully flew the predecessor mission and provided sub-arcsecond pointing from a high altitude balloon, the transition to spaceflight aboard the ISS introduces many new challenges. This study proposes the introduction of both a modified state observer and a neural network controller to address these challenges, replacing the traditional PID controller used in the past. Results show that pointing precision and stability can be improved using the new methodology.

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* Ph.D. Student, Mechanical and Aerospace Engineering Department, Missouri University of Science and Technology, 400 W 13th St, Rolla, MO 65409-0050, USA.
† Professor of Aerospace Engineering and Dean's Educator Scholar, Mechanical and Aerospace Engineering Department, Missouri University of Science and Technology, 400 W 13th St, Rolla, MO 65409-0050, USA.
‡ Curators' Distinguished Professor, Mechanical and Aerospace Engineering Department, Missouri University of Science and Technology, 400 W 13th St, Rolla, MO 65409-0050, USA.

**AAS 20-717**

# LIGHT CURVE ATTITUDE ESTIMATION USING THE VIEWING SPHERE

**A. Burton[*] and C. Frueh[†]**

In cases where no resolved images can be obtained of a space object, it is often effective to use light curve measurements to estimate its attitude. Many methods for doing this rely on assumptions about the rotation of the object. This paper examines a method for obtaining the attitude time history of an unresolved object with general rotation, without any a priori information about the object's attitude or motion, and without restricting the attitude solutions to specific attitude profiles. The shape and reflective properties of the object are assumed to be known. The concept of the viewing sphere is used to aid in finding possible orientations of the object for each measurement. The preliminary concept is illustrated using the simple case of constant rotation about a fixed axis as a null-hypothesis test. The estimated attitude time histories are compared to Williams' method for determining a single axis attitude profile.

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[*] Graduate Student, School of Aeronautics and Astronautics, Purdue University 701 W. Stadium Ave. West Lafayette, IN 47907-2045, USA. E-mail: burton30@purdue.edu.
[†] Associate Professor, School of Aeronautics and Astronautics, Purdue University 701 W. Stadium Ave. West Lafayette, IN 47907-2045, USA. E-mail: cfrueh@purdue.edu. AIAA Member.

AAS 20-720

# DYNAMICS AND CONTROL FOR TRAJECTORY TRACKING OF PARALLEL SPACE CAPTURING ROBOT

**Fei Liu,[*] Quan Hu,[†] Lei Liu,[‡] Xiaohui Li,[§] Weihui Liu,[**] Wen Wen,[††] and Jingchao Zhao[‡‡]**

Parallel mechanism is widely used in aerospace engineering because of its high structural rigidity, large load capacity, and precise motion ability. In this work, a parallel mechanism is utilized as the actuator of a free-floating robot for on-orbit target capturing. The target can be captured by the interior space of the mechanism. The resultant system is named as the parallel space robot (PSR). The PSR's dynamics model is established from multibody perspective through Maggi-Kane's method. A finite time adaptive controller and a torque distribution law are developed for the trajectory tracking. Numerical simulations demonstrate the effectiveness and efficiency of the given control scheme for PSR.

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[*] PhD Candidate, School of Aerospace Engineering, Beijing Institute of Technology, Beijing, 100081, China.
[†] Assistant Professor, School of Aerospace Engineering, Beijing Institute of Technology, Beijing, 100081, China.
[‡] Researcher, Beijing Institute of Control Engineering, Beijing, 100080, China.
[§] Researcher, Beijing Institute of Control Engineering, Beijing, 100080, China.
[**] Engineer, Beijing Institute of Control Engineering, Beijing, 100080, China.
[††] Engineer, Beijing Institute of Control Engineering, Beijing, 100080, China.
[‡‡] Engineer, Beijing Institute of Control Engineering, Beijing, 100080, China.

AAS 20-723

# INTEGRATED POWER, ATTITUDE, AND VIBRATION CONTROL OF GYROELASTIC BODY

Chuandong Guo* and Quan Hu†

Variable speeds control moment gyros (VSCMGs) are a kind of angular momentum exchange devices. It contains a rotor with high rotating speeds. The direction and the magnitude of the rotor's angular momentum can be simultaneously tuned. When distributing a set of VSCMGs on a flexible structure, they could simultaneously produce control torques for attitude control and modal forces for vibration suppression. Meanwhile, the high spinning rotor in the VSCMGs can be used for energy storage. Thus, an integrated power, attitude, and vibration control system (IPAVCS) for a free flexible structure can be obtained. In this work, the control scheme for IPAVCS is developed. A nonlinear controller is first designed to calculate the desired attitude control torques and vibration suppression modal forces for attitude stabilization and vibration suppression. Then, a robust pseudoinverse gimbal steering law and a pseudoinverse rotor acceleration law are developed to generate the desired control input and meet the power requirement, respectively. Numerical examples are conducted to verify the effectiveness of the proposed control scheme.

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* Ph.D. Student, Beijing Institute of Technology, School of Aerospace Engineering, 100081 Beijing, People's Republic of China. E-mail: guochuandong@bit.edu.cn.

† Assistant Professor, Beijing Institute of Technology, School of Aerospace Engineering, 100081 Beijing, People's Republic of China. E-mail: huquan2690@bit.edu.cn. Corresponding Author.

AAS 20-729

# DEMONSTRATION SCIENCE EXPERIMENT ADAPTIVE CONTROL EXPERIMENT PLAN & PRELIMINARY SYSTEM IDENTIFICATION

**Lawrence D. Davis*** **and Andrew J. Sinclair†**

The Adaptive Control Experiment onboard the Demonstration Science Experiment mission will validate attitude control technologies for highly flexible spacecraft. The experiment uses a modular approach to perform on-orbit system identification of the flexible-body dynamics, and then perform automated controller design. Experiment results so far have verified boom deployments and identified the low and high frequency dynamics. Upcoming experiment plans include implementing closed-loop control, with the goal of factor of ten increase in control bandwidth relative to the nominal attitude controller.

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* SRC, 7502 Round Pond Road, North Syracuse, NY 13212, USA.
† Senior Aerospace Engineer, Space Vehicles Directorate, Air Force Research Laboratory, 3550 Aberdeen Ave SE, Kirtland AFB, NM 87117, USA.

AAS 20-732

# OPTIMAL ATTITUDE MANEUVERS USING MODEL PREDICTIVE CONTROL AND CHEBYSHEV-PICARD METHODS

Adrian Juarez,* Ahmad Bani Younes,† Ahmed Atallah,‡ and Robyn M. Woollands§

Model predictive control is a powerful methodology that involves repeatedly solving an optimization problem over a moving time horizon, using predictions of the system's future behavior and response. Model predictive control is especially useful for handling model and parameter uncertainty in real-world applications, and it has become a widespread solution methodology in industry. Typically, the nonlinear system dynamics are approximated by linearized dynamics and the controller, which is designed based on the linear system, is used to control the nonlinear system. This approach requires solution of the Riccati equation. The key contribution of this paper is the development of a model predictive controller, that operates directly on the nonlinear system dynamics, for optimal spacecraft attitude control. The optimal control formulation leads to a boundary value problem where the initial costates must be iterated to solve for the optimal control that drives the system to the desired final attitude. A unique formulation of the Chebyshev-Picard boundary value solver is implemented, whereby the state and costate equations are simultaneously integrated forward and backwards respectively over the finite receding horizon. We present simulation results for an attitude maneuver using our new algorithm and compare the performance to that of the classical Linear Quadratic Regulator, as well as a shooting method that utilizes MATLAB's *fsolve* and *ode78*.

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* Graduate Research Assistant, Aerospace Engineering, San Diego State University, San Diego, CA, USA.
† Assistant Professor, Aerospace Engineering, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182-1308, USA. AIAA Member.
‡ Graduate Research Assistant, Aerospace Engineering, San Diego State University, San Diego, CA, USA.
§ Assistant Professor, Aerospace Engineering, University of Illinois, Urbana-Champaign, IL 61801, USA.

AAS 20-735

# STATIC ATTITUDE ESTIMATION FROM LIGHT INTENSITY MEASUREMENTS: A HEURISTIC APPROACH

**Stephen R. Gagnon[*] and John L. Crassidis[†]**

This paper explores the possibility of generating an attitude estimate for a space object from a set of static light intensity measurements using heuristic optimization techniques. The goal is to minimize the difference between a true observed intensity and an intensity calculated based on an estimated attitude along with knowledge of object geometry. Multiple measurements are required for observability, and multiple combinations of observers are considered. A particle swarm algorithm is implemented to identify the attitude that minimizes the intensity error. Several extensions to the standard particle swarm algorithm are considered, including a cluster-based global topology and cooling schedules for several heuristic parameters. Measurements are generated using the Phong anisotropic light reflection model. Once a good attitude estimate is obtained, it can be used to initialize an attitude filter. An unscented Kalman filter is implemented, and a range of angular rate errors are considered.

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[*] Graduate Student, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, NY 14260-4400, USA. E-mail: srgagnon@buffalo.edu.

[†] SUNY Distinguished Professor and Samuel P. Capen Chair Professor, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, NY 14260-4400, USA. Fellow AAS.
E-mail: johnc@buffalo.edu.

AAS 20-738

# COMPARISON OF DIFFERENT MACHINE LEARNING METHODS FOR MACHINE LEARNING ENHANCED GYRO CALIBRATIONS

**Hao Peng[*] and Xiaoli Bai[†]**

In this paper, a recently developed machine learning (ML) enhanced gyro calibration method is further explored. This new framework is based on the standard attitude and gyro bias EKF estimator. A time series about the gyro measurement error is extracted from the estimation data and then used to train ML models that can provide better accuracy to calibrate the real-time rate measurement. This paper summarizes the results of the multilayer perceptron (MLP), convolutional neural network (CNN), recurrent neural network (RNN), and Gaussian processes (GPs) models. These four models are based on different principles to handle the time series problem. Results show that all the four methods generate gyro calibrations more accurate than the standard EKF in the simulated situation. Moreover, they could also generate reliable uncertainty information about the correction.

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[*] Postdoctoral Associate, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ 08854, USA. E-mail: astro.H.Peng@gmail.com.
[†] Associate Professor, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ 08854, USA. E-mail: xiaoli.bai@rutgers.edu.

# 3D ATTITUDE SYNCHRONIZATION CONTROL WITH COULOMB INTERACTIONS

**John Galjanic[*] and Dongeun Seo[†]**

This study generalizes the previous work in Relative Attitude Control of Two Spacecraft Using Electrostatic Interactions to the three-dimensional case. This study models two identical spacecraft and seeks to control their relative attitude in three-dimensional rotation using electrostatic torques. Simulation results indicate that this system is controllable with the given assumptions. Future work will consider the optimal distribution of the spacecraft charges to create the electrostatic control torque.

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[*] Graduate Student, Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA. E-mail: galjanij@my.erau.edu.
[†] Associate Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA. E-mail: seod@erau.edu.

AAS 20-755

# MODEL-PREDICTIVE ATTITUDE CONTROL FOR FLEXIBLE SPACECRAFT DURING THRUSTER FIRINGS

Kevin Tracy* and Zachary Manchester†

We present a model-predictive control technique for attitude control of flexible spacecraft during thruster firings. Due to the flexibility of the spacecraft, control laws designed under the rigid-body assumption can perform poorly during thruster-induced deflections. A model-predictive controller, in contrast, can leverage a greater understanding of the flexible-body dynamics and actuator constraints, and can achieve significantly better pointing performance than traditional control laws. To demonstrate the effectiveness of this control strategy, we compare the MPC controller with an LQR feedback controller during a thruster firing in the presence of noise and model uncertainty. The MPC controller performs significantly better, enabling lighter and more flexible spacecraft designs.

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* Department of Mechanical Engineering, Stanford University, 496 Lomita Mall, Stanford, CA 94305, USA.
† Department of Aeronautics and Astronautics Engineering, Stanford University, 496 Lomita Mall, Stanford, CA 94305, USA.

AAS 20-769

# CALIBRATED APPROXIMATIONS OF ERROR KINEMATICS FOR ATTITUDE PARAMETERIZATIONS

Eric A. Butcher,* Aniket Bire,† and Andrew J. Sinclair‡

Calibrated approximations of the nonlinear attitude error kinematics for various attitude parameterizations are derived. For this purpose, the equivalence of the linearized equations of motion, related through linearized transformations, is demonstrated assuming either additive or multiplicative error definitions. This equivalence is used to develop calibrated linearized solutions for coordinates with higher nonlinearity indices that utilize the linearized solutions for coordinates with lower nonlinearity indices and thus provide greater accuracy than the traditional linearized solution. Additionally, the inverse of the calibration process is used to develop a more accurate decalibrated solution.

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* Professor, Aerospace and Mechanical Engineering, University of Arizona, Tucson, AZ 85721, USA.
E-mail: ebutcher@email.arizona.edu.
† Graduate Student, Aerospace and Mechanical Engineering, University of Arizona, Tucson, AZ 85721, USA.
‡ Senior Aerospace Engineer, Air Force Research Laboratory, Space Vehicles Directorate, Albuquerque, NM, 87117, USA.

# DYNAMICAL SYSTEMS THEORY APPLIED TO SPACE FLIGHT

AAS 20-434

# HILL'S LUNAR THEORY REVISITED

**William E. Wiesel***

A Hill-like dynamical system is posed, and used to construct a Hill periodic orbit and Floquet modes for the orbit of the Moon. The dynamics is conservative if the earth's orbital eccentricity is ignored, and periodic if it is included. The best fit of the Hill periodic orbit plus Floquet modes has a disappointingly large RMS error of ≈ 6000 km when fit to ephemeris data from the NASA Horizons system. But agreement is to within a few kilometers over at least a year when the earth's eccentricity is included. Long integrations of this set of initial conditions are then carried out to see if the lunar orbit lies within to an invariant torus. There is strong evidence that it does.

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* Professor of Astronautical Engineering, Department of Aeronautics and Astronautics, Air Force Institute of Technology, 2950 Hobson Way, Wright-Patterson AFB, OH 45433, USA. Tel.: +937-255-3636, Fax: +937-656-4032, E-mail: William.Wiesel@afit.edu.

**AAS 20-459**

# TECHNICAL IMPLEMENTATION OF THE CIRCULAR RESTRICTED THREE-BODY MODEL IN STK ASTROGATOR

**Cody Short,[*] Amanda Haapala,[†] and Natasha Bosanac[‡]**

Spacecraft trajectory design is captivating: it is challenging, intriguing, creative, occasionally tedious, and ultimately pretty cool. While some of this characterization is subjective, it is language that is typical for practitioners of the associated arts. One thing that is much more objective is that trajectory design is a process, and this process is often iterative. Currently, the process frequently begins with lower-fidelity, yet representative, models to compute initial guess data for phases of the trajectory itinerary, with incrementally more complex models expanding understanding of the design space. An example of a model that inherently reflects such an incremental increase in fidelity is the Circular Restricted Three-body Problem (CR3BP), which still represents a simplification from real-world systems but does so at the advantage of rich mathematical theory. This model offers reduced numerical and conceptual complexity yet yields solutions that can capture the governing behaviors of the underlying higher-fidelity systems. This paper is intended to establish the relevance of the incorporation of the mathematical framework of the CR3BP model into the Systems Tool Kit (STK) Astrogator module from Analytical Graphics, Inc. (AGI), to discuss the unique implementation requirements posed by this effort and to offer verification and validation of this implementation.

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[*] Astrodynamics Software Engineer, Analytical Graphics, Inc., 220 Valley Creek Blvd., Exton, PA 19341, USA.
[†] Mission Design Engineer, Astrodynamics and Controls Group, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA.
[‡] Assistant Professor, Colorado Center for Astrodynamics Research, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, CO 80309, USA.

**AAS 20-462**

# MOON-TO-MOON TRANSFER METHODOLOGY FOR MULTI-MOON SYSTEMS IN THE COUPLED SPATIAL CIRCULAR RESTRICTED THREE-BODY PROBLEM

**David Canales,[*] Kathleen C. Howell,[†] and Elena Fantino[‡]**

Given the interest in future space missions devoted to the exploration of key moons in the Solar System and that may involve libration point orbits, an efficient design strategy for transfers between moons is introduced that leverages the dynamics in these multi-body systems. A general methodology for transfer design between the moons in any given system is developed within the context of the circular restricted three-body problem, useful regardless of the orbital planes in which the moons reside. A simplified model enables analytical constraints to determine the feasibility of a transfer between two different moons moving in the vicinity of a common planet.

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[*] Ph.D. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: dcanales@purdue.edu.

[†] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: howell@purdue.edu.

[‡] Assistant Professor at Department of Aerospace Engineering, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates. E-mail: elena.fantino@ku.ac.ae.

AAS 20-482

# A UNIQUE APPROACH TO ACHIEVING SIZE-CONSTRAINED QUASI-HALO ORBITS FOR THE ROMAN SPACE TELESCOPE

Lauren Schlenker,* Ariadna Farrés,† Cassandra Webster,‡
Jennifer Donaldson,§ and Robert Pritchett**

The Nancy Grace Roman Space Telescope (RST) is an infrared space observatory planned for launch in the mid-2020's. The launch window design for RST is subject to a wide variety of simultaneous requirements that require careful consideration and control of mission orbits and the trajectories used to achieve them. This work describes an innovative methodology that blends classical methods with modern manifold approaches and numerical optimization to flexibly determine optimal transfers to desirable mission orbits for any day of the year. Solutions found with this highly automated strategy are guaranteed to meet requirements by construction. Results show that RST can launch for 80% of the year using maneuvers that are well within the fuel budget, significantly reducing cost and risk to the mission.

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* NASA Goddard Space Flight Center, 8000 Greenbelt Road, Greenbelt, MD 20771, USA.
E-mail: lauren.schlenker@nasa.gov.
† NASA Goddard Space Flight Center, University of Maryland Baltimore County, 1000 Hilltop Cir, Baltimore, MD, 21250, USA. E-mail: ariadna.farresbasiana@nasa.gov.
‡ NASA Goddard Space Flight Center, 8000 Greenbelt Road, MD 20771, USA. E-mail: cassandra.webster@nasa.gov.
§ NASA Goddard Space Flight Center, 8000 Greenbelt Road, MD 20771, USA.
E-mail: jennifer.e.donaldson@nasa.gov.
** Purdue University, 701 West Stadium Avenue, West Lafayette, IN 47907, USA. E-mail: pritcher@purdue.edu.

AAS 20-489

# UNSUPERVISED LEARNING TO AID VISUALIZATION OF HIGHER-DIMENSIONAL POINCARÉ MAPS IN MULTI-BODY TRAJECTORY DESIGN

**Stefano Bonasera[*] and Natasha Bosanac[†]**

In spatial or nonautonomous models of multi-body systems, it is often challenging to explore the solution space via a higher-dimensional Poincaré map. In this paper, unsupervised learning techniques are used to improve analysis and visualization of Poincaré maps: clustering is used to group trajectories by their geometry, while manifold learning is used for both visualization, cluster correction and correlation. This approach is demonstrated using three examples: studying the persistence of solutions across various values of the independent variables in the elliptic restricted three-body problem and the point mass ephemeris models, and across models of increasing fidelity.

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[*] Ph.D. Student, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado, 3775 Discovery Dr., Boulder, CO 80303, USA. E-mail: stefano.bonasera@colorado.edu.
[†] Assistant Professor, Ann and H.J. Smead Aerospace Engineering Sciences, 3775 Discovery Dr., University of Colorado, Boulder, CO 80303, USA. E-mail: natasha.bosanac@colorado.edu.

**AAS 20-498**

# BINARY INTEGER LINEAR PROGRAMMING FORMULATION FOR OPTIMAL SATELLITE CONSTELLATION RECONFIGURATION

**Hang Woon Lee[*] and Koki Ho[†]**

Satellite constellations are commonly designed for fixed mission requirements. However, these systems are often subject to change in mission operations. This paper integrates the constellation transfer problem and the constellation design problem that are otherwise independent and serial in nature. Building upon the integrated model, this paper provides a solution to the following general problem statement. Suppose an existing satellite constellation system, a group of satellites with some form of shared orbital characteristics, is undertaking a reconfiguration process from its initial configuration to a final configuration due to variations in mission operations. The problem is to find the specifications of the reconfiguration process that maximizes the utility. An illustrative example is conducted to demonstrate the value of the framework.

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[*] Ph.D. Student, National Science Foundation Graduate Research Fellow, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, USA.

[†] Assistant Professor, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, USA.

AAS 20-568

# ANALYSIS OF STOCHASTIC NEARLY-INTEGRABLE DYNAMICAL SYSTEMS USING POLYNOMIAL CHAOS EXPANSIONS

**Matteo Manzi* and Massimiliano Vasile***

In this paper we propose the use of dynamic intrusive Polynomial Chaos Expansions (dPCE) to study some properties of nearly-integrable systems in orbital mechanics, where the perturbation is stochastic; we focus on random-walk type of perturbations.

We use a simple Weiner process to model the stochastic component of the perturbation and a truncated Karhunen–Loève expansion of the Weiner process to allow the treatment with Polynomial Chaos. In particular, we use dynamic Polynomial Chaos, where the integration time is divided in segments and PCEs are restarted on each segment, to keep the number of coefficients of the Karhunen–Loève expansion contained.

We first study a stochastic version of the Hénon-Heiles system, we then consider the motion of a stochastically perturbed satellite in geostationary orbit. For both problems we show evidence of diffusion induced by the stochastic perturbation.

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* Aerospace Centre of Excellence, University of Strathclyde, Glasgow, UK.

AAS 20-570

# GPGPU IMPLEMENTATION OF PINES' SPHERICAL HARMONIC GRAVITY MODEL

**J. R. Martin[*] and H. Schaub[†]**

Efficient, analytic gravity algorithms are of the upmost importance for astrodynamics research. Such algorithms underlie all satellite simulation software to which researchers and missions have grown increasingly dependent. As these software grow increasingly high-fidelity – accommodating more complex environments, higher density constellations, and more realistic perturbations – there grows a need to revisit their core gravity algorithm to ensure it does not become a bottleneck. Namely as gravity field models continue to improve, simulations will become increasingly burdened by traditional, serial algorithms – requiring astrodynamicists to trade computation speed for model accuracy. In efforts to bypass this tradeoff, this paper investigates a general purpose graphics processing unit (GPGPU) implementation of Pines' spherical harmonic gravity algorithm using Vulkan — an emergent, cross-platform graphics and compute API.

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[*] NSF Graduate Research Fellow, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, CO 80309, USA.

[†] Glenn L. Murphy Chair of Engineering, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, CO 80309, USA. AAS Fellow, AIAA Fellow.

**AAS 20-585**

# DATA-DRIVEN SPARSE APPROXIMATION FOR THE IDENTIFICATION OF NONLINEAR DYNAMICAL SYSTEMS: APPLICATION IN ASTRODYNAMICS

**Damien Guého,[*] Puneet Singla,[†] and Robert G. Melton[‡]**

This work aims to provide a unified and automatic framework to discover governing equations underlying a dynamical system from data measurements. In an appropriate basis, and based on the assumption that the structure of the dynamical model is governed by only a few important terms, the equations are sparse in nature and the resulting model is parsimonious. Solving a well-posed constrained one-norm optimization problem, we obtain a satisfactory zero-norm approximation solution and determine the most prevalent terms in the dynamic governing equations required to accurately represent the collected data. Considering the well-known problem of identifying the central force field from position only observation data, we validate the developed approach by comparing the sparse solution with classical least-squares regression techniques and deep learning approaches.

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[*] Graduate Student, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: djg76@psu.edu.

[†] Associate Professor, AIAA Associate Fellow, AAS Fellow, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: psingla@psu.edu.

[‡] Professor, AIAA Associate Fellow, AAS Fellow, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: rgmelton@psu.edu.

AAS 20-637

# CONSTRUCTION OF BALLISTIC LUNAR TRANSFERS LEVERAGING DYNAMICAL SYSTEMS TECHNIQUES

**Stephen T. Scheuerle,* Brian P. McCarthy,† and Kathleen C. Howell‡**

Ballistic lunar transfers exploit the gravitational influence of the Earth, Moon, and Sun to reduce propellant costs associated with transfers from the Earth to the lunar vicinity via heliocentric space. This investigation considers the computation of lunar transfers in the Circular Restricted Three-body Problem (CR3BP) and the Bicircular Restricted Four-body Problem (BCR4BP). Families of transfers are constructed by leveraging dynamical systems theory techniques. Feasible solutions are delivered that reach various destinations nearby the Moon, including conic and libration point orbits. Additionally, energy properties formulated relative to these models characterize different transfer geometries. These strategies provide insight into the process for selection and construction of ballistic lunar transfers for trajectory design.

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* Graduate Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: sscheuer@purdue.edu.
† Ph.D. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: mccart71@purdue.edu.
‡ Hsu Lo Distinguished Professor, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: howell@purdue.edu. Fellow AAS; Fellow AIAA.

AAS 20-724

# TRANSITIONS BETWEEN QUASI-PERIODIC ORBITS NEAR RESONANCES IN THE CIRCULAR RESTRICTED THREE-BODY PROBLEM

**Stefano Bonasera*** **and Natasha Bosanac†**

Natural transitions between near-resonant orbits occur throughout our solar system and are exploited during mission design. To study the vast solution space associated with these natural transitions, this paper focuses on constructing heteroclinic connections between families of quasi-periodic orbits near resonances in the Earth-Moon circular restricted three-body problem. The hyperbolic invariant manifolds associated with quasi-periodic orbits are examined using an alternative representation of a Poincaré map that is constructed using manifold learning, a technique used for dimension reduction, to simplify visualization and analysis. Initial guesses, identified from this map, are corrected and input to a continuation scheme to examine the existence of natural transfers with a similar geometry between various quasi-periodic orbits along each family. This approach and analysis is demonstrated for natural transitions from quasi-periodic orbits near the interior 3:2 resonance to quasi-periodic orbits near the exterior 1:2 resonance.

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* Ph.D. Student, Ann and H.J. Smead Aerospace Engineering Sciences, 3775 Discovery Dr., Boulder, CO 80303, USA. E-mail: stefano.bonasera@colorado.edu.

† Assistant Professor, Ann and H.J. Smead Aerospace Engineering Sciences, 3775 Discovery Dr., Boulder, CO 80303, USA. E-mail: natasha.bosanac@colorado.edu.

# ARTEMIS PROGRAM

AAS 20-422

# ATTITUDE CONTROL APPROACH FOR DESCENT AND TRANSFER ELEMENTS DURING LONG-TERM BALLISTIC COAST*

**Jing Pei† and Carlos M. Roithmayr‡**

The Transfer Element and Descent Element, two parts of the Human Landing System, will travel separately from low Earth orbit to a lunar near-rectilinear halo orbit by way of a low-energy ballistic lunar transfer trajectory lasting three to four months. During the transfer a pair of solar arrays must face the Sun; they are sized by assuming a pointing error of 15 deg. For the purpose of thermal control, the vehicle will perform a slow rotation, referred to as barbecue roll, in which its angular velocity is approximately parallel to the roll axis. An approach to fuel-efficient attitude control is presented for these spacecraft, each of which is nearly axisymmetric. The approach involves periodically firing reaction control system thrusters to change the direction of the spacecraft's angular momentum and then allowing the attitude to evolve without active control until the direction of angular momentum must be changed again in order to keep the solar arrays facing the Sun. This approach requires substantially less propellant than the traditional technique of using a phase-plane controller together with thrusters to keep attitude error within required limits. The approach satisfies pointing requirements in the presence of sensor noise and environmental disturbance torque.

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† Aerospace Engineer, Vehicle Analysis Branch, NASA Langley Research Center, Hampton, Virginia, 23681, USA.

‡ Senior Aerospace Engineer, Vehicle Analysis Branch, NASA Langley Research Center, Hampton, Virginia, 23681, USA.

AAS 20-511

# THE BEHAVIOR OF HIGH-VELOCITY DUST GENERATED BY LANDER PLUMES IN THE LUNAR ENVIRONMENT

M. M. Wittal,[*] J. R. Phillips III,[†] P. T. Metzger,[‡] B. Link,[§]
J. G. Mantovani,[**] and D. Batcheldor[††]

Lunar lander plumes are known to accelerate fine dust to speeds exceeding 2 km $s^{-1}$, and the resultant ejecta may remain in lunar orbit for extended periods of time. Such ejecta could become hazardous to objects in lunar orbit as well as systems on the surface. In order to understand the impact on orbiting lunar infrastructure such as Gateway, as well as assets on the lunar surface, here we consider the dynamics of the resultant high-velocity plume ejecta. Initial conditions were set by the expected near-term lunar activity and the known cone of accelerated dust generated by previous lunar landings. The effects of regular 3-body gravitation, solar radiation pressure, and electric field are included in the model. It is found that although the majority of sub-μm dust is carried away by solar wind and electric fields, about ~10% of the dust between 1.7 km $s^{-1}$ and 2.3 km $s^{-1}$ reimpacts the surface, much of it near the landing site. The hazard posed by that debris is a function of lander mass and distance from the landing site. The Gateway, when orbiting in the nominal NRHO at the time of a landing, is not expected to be significantly affected by the dust. However, other spacecraft in less elliptic orbits may be at greater risk.

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[*] NASA Kennedy Space Center (KSC) Granular Mechanics and Regolith Operations (GMRO) Laboratory & Gateway Logistics Service (GLS), NASA KSC Mail-code UB-E, Kennedy Space Center, FL 32899 & Embry-Riddle Aeronautical University, 600 S Clyde Morris Blvd, Daytona Beach, FL 32114, USA.
[†] NASA Kennedy Space Center (KSC) Electrostatics and Surface Physics Laboratory (ESPL), NASA KSC Mail-code UB-G, Kennedy Space Center, FL 32899, USA.
[‡] University of Central Florida, Florida Space Institute, 12354 Research Parkway, Suite 214, Orlando, Florida 32826, USA.
[§] SURA, LASSO-URS Federal Services Inc., Kennedy Space Center, Florida 32899, USA.
[**] NASA Kennedy Space Center (KSC) Granular Mechanics and Regolith Operations (GMRO) Laboratory, NASA KSC, Mail-code UB-E, Kennedy Space Center, Florida 32899, USA.
[††] SURA, LASSO-URS Federal Services Inc., Kennedy Space Center, Florida 32899, USA.

AAS 20-519

# SPACE LAUNCH SYSTEM FLIGHT READINESS ANALYSIS CYCLE APPROACH

**Evan Anzalone, Ivan Bertaska, A. Scott Craig, Young Kim, Paul Von der Porten, Daniel Tyler,[*] Ben Burger, Jimmy Compton, Ashley Hill, Thomas Park, John Wall,[†] Adam Harden, Jayden Hauglie, Matthew Hawkins and Seth Thompson[‡]**

In order to provide mission assurance and performance verification of the Space Launch System, the Flight Readiness Analysis Cycle (FRAC) has been developed to provide evidence to support Flight Readiness Review activities. This cycle represents an integrated approach to vehicle assessment, including multiple partners and analysis groups. In order to facilitate launch date variations, the process utilizes a rolling target to phase analysis product deliveries, ensuring adequate time for certification prior to launch. This paper will provide an overview of the FRAC process, including integration with external partners and lessons learned from the initial implementation of FRAC analysis.

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[*] NASA/Marshall Space Flight Center, Huntsville, AL 35812, USA.
[†] NASA/ESSCA/Dynamics Concepts, Inc, Huntsville, AL 35812, USA.
[‡] NASA/ESSCA/Jacobs Space Engineering Group, Huntsville, AL 35806, USA.

**AAS 20-520**

# POST-FLIGHT RECONSTRUCTION APPROACH FOR SPACE LAUNCH SYSTEM ARTEMIS I MISSION

**Evan Anzalone, Greg Dukeman, Mike Fritzinger,[*] Tim Curry, Thomas Park,[†] Charlie Hall,[‡] and Frank Willis[§]**

Upon completion of the first Space Launch System (SLS) flight, NASA personnel will begin post-flight analyses. Telemetry from across the vehicle will be combined with external radar tracking and environmental observation data in order to close validation criteria. This paper will describe the approach taken by the SLS team to integrate flight data from multiple flights sources into Best Estimated Trajectory (BET), pre-flight simulation and testing results, primary sources of uncertainty, and path towards processing flight results. This paper also includes a brief description of algorithms and approaches to estimate as-flown vehicle parameters such as booster specific impulse, booster (and core) thrust multipliers and dry mass.

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[*] NASA/Marshall Space Flight Center/EV42, Huntsville, AL 35812, USA.
[†] NASA/Marshall Space Flight Center/Jacobs/ESSCA/Dynamic Concepts, Inc., Huntsville, AL 35806, USA.
[‡] NASA/Marshall Space Flight Center/Jacobs/ESSCA/Quantitech, Huntsville, AL 35806, USA.
[§] NASA/Marshall Space Flight Center/Jacobs/ESSCA/Bevilacqua Research Corporation, Huntsville, AL 35805, USA.

**AAS 20-535**

# MISSED THRUST ANALYSIS AND DESIGN FOR LOW THRUST CISLUNAR TRANSFERS

**Steven L. McCarty[*] and Daniel J. Grebow[†]**

This paper details the analysis of the missed thrust problem for low thrust cislunar transfers. Missed thrust analysis is completed for a reference NRHO to DRO transfer that is designed to maximize the final mass without consideration of robustness to unexpected loss of thrust. A new missed thrust design method is presented to include the robustness of the transfer as part of the optimization problem by including a minimal number of branching trajectories tied to the start of thrust arcs in the reference transfer and optimizing them all simultaneously. Results from variations of this approach are presented for and compared to the reference transfer designed without consideration for missed thrust. The results show that this new method can reduce the additional propellant required for recovery from an unexpected 7-day outage by up to 90% without significant increase to the propellant required to complete the reference transfer.

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[*] Mission Design Engineer, Mission Architecture and Analysis Branch, NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, USA.
[†] Mission Design Engineer, Outer Planet Mission Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

AAS 20-589

# SPACE LAUNCH SYSTEM ENGINE OUT CAPABILITIES

**A. S. Craig,[*] J. E. Hauglie,[†] M. J. Hawkins,[‡] and J. J. Hays[§]**

NASA's Space Launch System (SLS) is being developed with the primary purpose of returning people to the Moon and eventually landing people on Mars. With these lofty goals, ensuring mission completion is paramount even in the event of an in-flight mishap. One possible mishap is the loss of an engine in flight. While SLS was not required to show full engine out capability, the program took an "assess to" approach to see when the launch vehicle could complete the mission after an engine failure versus when the launch vehicle targets required a down-mode to an alternate mission target to ensure at least some flight objectives were complete, or at a minimum ensure safe return of Orion and the Crew. While this paper will focus on Artemis I, an uncrewed mission, some comparisons will be made to how the engine out capability will change for the subsequent Crewed flights of SLS and Orion.

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[*] EV42/Guidance Navigation and Mission Design Branch, NASA, Marshall Space Flight Center, Huntsville, AL 35812, USA.

[†] Jacobs Engineering, Jacobs ESSCA Group, Huntsville, AL 35812, USA.

[‡] Jacobs Engineering, Jacobs ESSCA Group, Huntsville, AL 35812, USA.

[§] EV42/Guidance Navigation and Mission Design Branch, NASA, Marshall Space Flight Center, Huntsville, AL 35812, USA.

**AAS 20-591**

# SPACE LAUNCH SYSTEM LAUNCH WINDOWS AND DAY OF LAUNCH PROCESSES

**A. S. Craig[*] and N. Ahmad[†]**

Lunar missions benefit from varying the launch azimuth as a function of launch time to allow longer launch windows with minimum performance impacts. This variable azimuth approach allows the vehicle to track the Moon's apparent motion due to Earth's rotation. The Space Launch System (SLS) Block 1 vehicle design requires the mission to launch into an elliptical parking orbit to provide sufficient energy to insert Orion into a Trans-Lunar Injection (TLI) orbit. The primary benefit of varying the launch azimuth, and as a result the achieved orbit inclination, allows the SLS Interim Cryogenic Propulsion Stage (ICPS) to perform its TLI burn closer to perigee and take advantage of performing a burn in a location where the burn will optimally raise apogee.

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

[†] Aerospace Engineer, 5910 Attitude Control System Branch, NASA, Goddard Space Flight Center, Greenbelt, MD 20771, USA.

AAS 20-592

# HUMAN LANDING SYSTEM STORABLE PROPELLANT ARCHITECTURE: MISSION DESIGN, GUIDANCE, NAVIGATION, AND CONTROL

**A. S. Craig, E. J. Anzalone,[*] M. R. Hannan,[†] B. L. Belanger,[‡] L. M. Burke,[§] G. L. Condon,[**] R. T. Joyce,[††] B. Mahajan,[‡‡] L. L. Means,[§§] and J. Pei[***]**

In preparation of the NextSTEP-2 Appendix H awards, NASA's Human Landing System (HLS) Program (HLSP) went through an abbreviated Design Analysis Cycle (DAC), or miniDAC, to characterize and quantify how a storable propellant design would affect and improve overall system performance of the Government reference design. As part of that miniDAC, HLSP ran multiple trade studies and assessments, including aspects of Mission Design, Flight Mechanics (FM), and Guidance, Navigation, and Control (GN&C). The storable propellant designs were assessed through the baseline mission targeting the Near Rectilinear Halo Orbit (NRHO) and several alternate staging orbits. This paper focuses on the FM and GN&C trades and assessments completed as part of the miniDAC as well as the GN&C elements of the miniDAC Master Equipment List (MEL) developed for the storable propellant lander configurations.

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[*] Guidance Navigation and Mission Design Branch, NASA, Marshall Space Flight Center, Huntsville, AL 35812, USA.
[†] Controls Systems Design and Analysis Branch, NASA, Marshall Space Flight Center, Huntsville, AL 35812, USA.
[‡] Bevilacqua Research Corporation, Jacobs ESSCA Group, Huntsville, AL 35812, USA.
[§] Mission Architecture and Analysis Branch, NASA, Glenn Research Center, Cleveland, OH 44135, USA.
[**] Flight Mechanics and Trajectory Design Branch, NASA, Johnson Space Center, Houston, TX 77058, USA.
[††] Space Mission Analysis Branch, NASA Langley Research Center, Hampton, Virginia, 23681, USA.
[‡‡] Odyssey Space Research LLC, Houston, TX 77058, USA.
[§§] Analytical Services Inc., Huntsville, AL 35812, USA.
[***] Vehicle Analysis Branch, NASA Langley Research Center, Hampton, Virginia, 23681, USA.

# THE CISLUNAR AUTONOMOUS POSITIONING SYSTEM TECHNOLOGY OPERATIONS AND NAVIGATION EXPERIMENT (CAPSTONE)

**Ethan W. Kayser,* Jeffrey S. Parker,† Matthew Bolliger,***
**Thomas Gardner,‡ and Bradley Cheetham§**

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) is a mission funded by the NASA Small Spacecraft Technology Program, scheduled to launch in 2021. It will traverse a low-energy Ballistic Lunar Transfer (BLT) and insert into a Near Rectilinear Halo Orbit (NRHO). CAPSTONE's objectives include demonstrating BLT and NRHO operations to inform fundamental exploration requirements and Gateway planning activities, as well as accelerating the infusion of the Cislunar Autonomous Positioning System (CAPS). CAPSTONE will demonstrate stationkeeping strategies within the NRHO and perform cross-link radiometric tracking with the Lunar Reconnaissance Orbiter (LRO).

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* Astrodynamicist, Advanced Space, 2100 Central Ave, #102, Boulder CO 80301, USA.
† Chief Technology Officer, Advanced Space, 2100 Central Ave, #102, Boulder CO 80301, USA.
‡ Director of Engineering, Advanced Space, 2100 Central Ave, #102, Boulder CO 80301, USA.
§ Chief Executive Officer, Advanced Space, 2100 Central Ave, #102, Boulder CO 80301, USA.

**AAS 20-604**

# SPACE LAUNCH SYSTEM DEPARTURE TRAJECTORY ANALYSIS FOR CISLUNAR AND DEEP-SPACE EXPLORATION

**Andrew F. Heaton[*] and Rohan Sood[†]**

The Space Launch System will insert Orion into different orbits for Artemis I and Artemis II. The Artemis program has considerations beyond the immediate mission of inserting Orion into its desired trajectory. Primarily, following separation from Orion, the Interim Cryogenic Propulsion Stage must be safely disposed, and another is that secondary payloads will be deployed only after Orion separation to ensure safety of the primary mission. The first consideration (ICPS disposal) constrains the latter (secondary payload trajectories). In this paper, we give an overview of the constraints and opportunities provided by Artemis missions for secondary payloads within the Earth-Moon system and beyond.

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[*] Team Lead, Guidance, Navigation and Mission Analysis Branch, NASA, EV42 Marshall Space Flight Center, Huntsville AL 35812, USA.
[†] Assistant Professor, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, 245 7th Ave, Tuscaloosa, AL 35401, USA.

**AAS 20-634**

# GUIDANCE MODIFICATIONS AND ENHANCEMENTS FOR SPACE LAUNCH SYSTEM BLOCK-1 IN SUPPORT OF ARTEMIS I AND BEYOND

**Matt Hawkins*[*] and Naeem Ahmad[†]**

NASA is currently building the Space Launch System (SLS) Block-1 launch vehicle for the Artemis I test flight. Design of the Artemis II mission, which will use the Block-1 vehicle to take astronauts around the moon for the first time in decades, is also underway. The Guidance, Navigation, and Controls (GN&C) algorithms will be largely similar for the two missions. However, the extensive simulation and testing campaign for Artemis I has revealed opportunities for improvements in the GN&C algorithms, allowing more effective use of the capabilities of the SLS vehicle, and enhancing safety for the astronauts aboard. This paper will describe several planned algorithm updates for the Artemis II mission. The updates enhance the Powered Explicit Guidance (PEG) algorithm and auxiliary guidance algorithms.

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[*] PhD, Aerospace Engineer, EV42/Guidance, Navigation, and Mission Analysis Branch, Jacobs Space Exploration Group, Huntsville, AL 35806, USA.

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

AAS 20-635

# ANALYSIS AND APPLICATION OF NOVEL AND HERITAGE ACCELERATION LIMITING ALGORITHMS FOR SLS ON ASCENT

Jason Everett,* John Wall,† and Naeem Ahmad‡

National Aeronautics and Space Administration (NASA) is currently building the Space Launch System (SLS) Block-1 launch vehicle, to be used as the crewed heavy-lift vehicle for the Artemis series of missions. The SLS Block-1 guidance subsystem[1] utilizes a non-linear algorithm derived from Shuttle heritage[2] for limiting the vehicle's induced maximum axial acceleration during ascent flight, known as g-limiting. Even though g-limiting has demonstrated stability and robustness through several design analysis cycles and the extensive Shuttle flight history, there are no available documents that demonstrate that this algorithm has been proven stable through conventional controls stability analysis. This paper highlights the nonlinear nature of g-limit, presents an alternative methodology to employ a linear version of this algorithm, performs assessment of selected linear gains using classical stability analysis and, conducts a comparison of both approaches through Six Degrees-of-Freedom (6-DOF) Monte Carlo (MC) simulations.

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* Aerospace Engineer, EV42/Guidance, Navigation, and Mission Analysis Branch, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA.
† Aerospace Engineer, EV41/Control System Design and Analysis Branch, Dynamic Concepts, Inc. (Jacobs ESSCA Group) Huntsville, AL 35806, USA.
‡ Aerospace Engineer, EV42/Guidance, Navigation, and Mission Analysis Branch, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA.

AAS 20-643

# NASA'S SPACE LAUNCH SYSTEM BEGINS INTEGRATION, STACKING IN PREPARATION FOR ARTEMIS I LAUNCH

**Kimberly Robinson*  and Robert W. Stough†**

The Artemis era of human lunar exploration is nearing take-off as NASA's new super heavy-lift launch vehicle, the Space Launch System (SLS), has begun assembly operations at Kennedy Space Center (KSC) in Florida as of June 2020. Launch of the Artemis I flight is planned for late 2021, and will mark the return of NASA's human spaceflight program to cislunar space. The SLS Block 1 vehicle, the initial variant to fly, is optimized for lunar missions with a proven propulsion system consisting of four liquid hydrogen (LH2)/liquid oxygen (LOX)-fed RS-25 engines and twin five-segment solid rocket boosters (SRBs). The Block 1 vehicle for the uncrewed Artemis I flight is fully manufactured and all elements are delivered or in transport to KSC at the time of writing, with the exception of the 64.6 m core stage. Technicians at Stennis Space Center (SSC) are putting the core stage through its paces in a series a "green run" tests, after which the stage will ship to KSC. In the meantime, Jacobs Technology technicians at KSC have started assembling the Artemis I SRBs for flight. With integration started on the Artemis I vehicle, manufacturing is progressing for the second and third vehicles, also Block 1 configurations. SLS is the backbone of NASA's Artemis program, designed to carry crew and cargo to the Moon and to evolve to progressively more powerful vehicles to meet NASA's needs for exploration of the Moon, Mars, and beyond. This paper will provide an overview of the capabilities of SLS as well as its manufacturing status for the Artemis I flight and beyond.

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* Dr., Manager, Payload Integration, NASA's Space Launch System, XP50, Marshall Space Flight Center, AL 35802, USA.

† Manager, SLS Utilization, NASA's Space Launch System, XP50, Marshall Space Flight Center, AL 35802, USA.

# ARTEMIS I TRAJECTORY DESIGN AND OPTIMIZATION

**Amelia L. Batcha,[*] Jacob Williams,[†] Timothy F. Dawn,[‡]
Jeffrey P. Gutkowski,[§] Maxon V. Widner,[**] Sarah L. Smallwood,[††]
Brian J. Killeen,[‡‡] Elizabeth C. Williams,[§§] and Robert E. Harpold[***]**

This paper presents the overall trajectory design and optimization process for NASA's Artemis I mission to send an uncrewed Orion vehicle to a lunar Distant Retrograde Orbit (DRO). The on-orbit trajectory begins at the Space Launch System (SLS) core separation and ends at the Orion service module Earth Entry Interface (EI) point. The details of the trajectory optimization process are presented, including design of nominal and extended mission options, launch windows, and abort options. Novel design techniques are also discussed to account for contingencies, such as using auxiliary thrusters to protect against main engine failure and applying trajectory shaping to mitigate or reduce eclipse durations.

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[*] EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058, USA.
[†] EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058, USA.
[‡] EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058, USA.
[§] EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058, USA.
[**] Jacobs Technology, Houston, TX 77058, USA.
[††] EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058, USA.
[‡‡] EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058, USA.
[§§] a.i. solutions, Houston, TX 77058, USA.
[***] ERC Inc., Houston, TX 77058, USA.

AAS 20-666

# GLOBAL POINT MASCON MODELS FOR THE MOON

**Sean McArdle[*] and Ryan P. Russell[†]**

Point mascon models are simple, parallizable alternatives to the standard spherical harmonics representation of the lunar gravity field. Gravity models are generated using masses located at nearly equally spaced positions on a spherical shell. The masses of each point are the solutions of a linear least squares minimization problem. The radius of the shell is chosen subject to a maximum magnitude bound on the individual masses. The models are fit to simulated measurement data derived from a high resolution spherical harmonics truth field. For runtime comparisons, corresponding spherical harmonics resolutions are chosen for each mascon model to match residual errors against the truth resolution. A 30,720 mascon model shows an order of magnitude speedup in gravity gradient evaluation when compared to the corresponding spherical harmonics resolution of 186 degrees.

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[*] Graduate Student, Aerospace Engineering, The University of Texas at Austin, 2617 Wichita Street, Austin, Texas 78712, USA. E-mail: seanmcardle14@utexas.edu.

[†] Associate Professor, Aerospace Engineering, The University of Texas at Austin, 2617 Wichita Street, Austin, Texas 78712, USA. E-mail: ryan.russell@utexas.edu.

AAS 20-682

# MULTIVARIABLE ROBUST CONTROL FOR THE POWERED DESCENT OF A MULTIBODY LUNAR LANDING SYSTEM

**Abhinav G. Kamath,[*] Francis F. Assadian,[†] and Stephen K. Robinson[‡]**

We present a novel approach to linear multivariable feedback control design, using Youla parameterization, to enable robust trajectory tracking for the powered-descent and safe-landing of a lunar lander with a gimbaled main engine. The extended Kane's equations for variable-mass systems are used to analytically model the nonlinear multibody dynamics of the lunar landing system. Propellant-optimal guidance state trajectories are generated by employing lossless convexification in a convex optimization framework. The procedure to design an internally stabilizing, computationally efficient, multiple-input multiple-output (MIMO) robust feedback control system is described. The closed-loop system is shown to possess guaranteed robustness to bounded uncertainties.

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[*] Graduate Student, Department of Mechanical and Aerospace Engineering, University of California, Davis, CA 95616, USA. Graduate Student Member, American Astronomical Society (AAS).

[†] Professor, Department of Mechanical and Aerospace Engineering, University of California, Davis, CA 95616, USA.

[‡] Director, UC Davis Center for Spaceflight Research; Professor, Department of Mechanical and Aerospace Engineering, University of California, Davis, CA 95616, USA.

**AAS 20-762**

# SUBOPTIMAL NONLINEAR MODEL PREDICTIVE CONTROL STRATEGIES FOR TRACKING NEAR RECTILINEAR HALO ORBITS*

**Andrew W. Berning Jr.,† Dominic Liao-McPherson,‡ Anouck Girard,§ and Ilya Kolmanovsky****

Near Rectilinear Halo Orbits (NRHOs), a subclass of halo orbits around the L1 and L2 Lagrange points, are promising candidates for future lunar gateways in cislunar space and as staging orbits for lunar missions. Closed-loop control is beneficial to compensate orbital perturbations and potential instabilities while maintaining spacecraft on NRHOs and performing relative motion maneuvers. This paper investigates the use of nonlinear model predictive control (NMPC) coupled with low-thrust actuators for station-keeping on NRHOs. It is demonstrated through numerical simulations that NMPC is able to stabilize a spacecraft to a reference orbit and handle control constraints. Further, it is shown that the computational burden of NMPC can be managed using specialized optimization routines and suboptimal approaches without jeopardizing closed-loop performance.

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† PhD Candidate, Aerospace Engineering, University of Michigan, 1221 Beal Avenue, Ann Arbor, MI 48109, USA.
‡ Research Fellow, Aerospace Engineering, University of Michigan, 1221 Beal Avenue, Ann Arbor, MI 48109, USA.
§ Associate Professor, Aerospace Engineering, University of Michigan, 1221 Beal Avenue, Ann Arbor, MI 48109, USA.
** Professor, Aerospace Engineering, University of Michigan, 1221 Beal Avenue, Ann Arbor, MI 48109, USA.

AAS 20-767

# PERFORMANCE MAPPING FOR DIRECT-INJECTION TRANSLUNAR PATHFINDER MISSIONS COMPATIBLE WITH HIGH-CADENCE, LOW-COST LAUNCH OPPORTUNITIES

Richard A. J. Hunter* and Brian C. Gunter†

Frequent translunar pathfinder missions may accelerate Artemis-era lunar exploration by increasing observational cadence and testing technologies that reduce risk of future discovery and flagship class missions. A cost-competitive commercial launch market and the rapid development cycle of small satellite architectures make pathfinders an accessible opportunity to universities and technology companies alike. This study characterizes performance for lunar flyby, orbit insertion, and landing pathfinder missions over an 18.6 year Earth-Moon nodal cycle. Through the simulation and statistical analysis of over 640,000 trajectories, optimal monthly mission masses and flight times between 2020 and 2038 have been mapped against lift capacities for modern commercial launch vehicles. Results demonstrate that correctly timed pathfinder missions may be flown to any lunar inclination, in any month, and can be supported by a broad spectrum of high-cadence, low-cost launch opportunities in the current commercial fleet.

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* Master's Graduate, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, North Avenue NW, Atlanta, GA 30332, USA. AIAA Professional Member.
† Associate Professor, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, North Avenue NW, Atlanta, GA 30332, USA. AIAA Senior Member.

# ASTEROID AND NON-EARTH ORBITING MISSIONS

AAS 20-414

# SOLAR ARRAY POINTING REQUIREMENTS DEVELOPMENT FOR THE PSYCHE SPACECRAFT*

**Peter C. Lai,† Havard F. Grip,‡ Dan Eldred,§ John Steven Snyder,** Denis Trofimov,†† and Ashley Madni‡‡**

Pointing the solar array to the Sun is critical for the power management in all solar-powered space missions. This is particularly true for NASA's Psyche mission, which will explore the large asteroid (16) Psyche orbiting the Sun at around 3 AU. Due to the large distance to the Sun, use of electric propulsion, and sophisticated scientific orbits at Psyche, the definition of this pointing accuracy became a challenging task for the spacecraft design, which involves the GNC, Power, and Thermal subsystems as well as Mission Design. This paper describes the story of how this complicated requirement development evolved for Psyche mission.

[View Full Paper]



† Corporate Engineer, LinQuest Corporation, 300 N. Pacific Coast Hwy, El Segundo, CA 90245, USA. AIAA Associate Fellow. Work was performed while Dr. Lai was a Flight System Systems Engineer at JPL.

‡ GN&C Analyst, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA.

§ GN&C Analysis Lead, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA.

** Propulsion & Power Systems Engineer, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA. AIAA Associate Fellow.

†† Power Systems Engineer, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA.

‡‡ Project Systems Engineer, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA.

AAS 20-442

# POINT-TO-POINT JUMPING DYNAMICS ON PHOBOS BY PROGRADE ORBIT FAMILIES

**Yuying Liang,* Nishanth Pushparaj,† Yasuhiro Kawakatsu,‡ and Masaki Fujimoto§**

This paper is devoted to a point-to-point jumping mechanism on Phobos surface by prograde orbit family. In the vicinity of Phobos, the distance retrograde orbit (DRO) family is used as long-term parking orbit for Phobos probe due to their large scale and strong stability. and prograde orbit families are critical to Phobos observation mission. The prograde orbits contain arcs outsides the surface of Phobos which is proved to have as low take-off and landing velocities as 2-4 m/s. Parameter analysis based on the invariant tori around stable prograde orbits shows that a time of flight up to 2 hours and maximum altitude of less than 4 km can be satisfied by properly selecting candidate arc. A jumping coverage angle as wide as 60 degree in longitude can be achieved. Thus, a point-to-point jumping mechanism is enabled by JAXA's MINERVA series that is small enough to be equipped on lander or rover and can provide an extra movement without thrust. In order to furtherly extend the jumping area, a patching package is developed to manage the trajectories based on the jumping arc archive of all prograde orbits. The feasibility of jumping arcs is analyzed and verified in Mars-ellipsoid model and applications to trajectory management is presented in high-fidelity model.

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* Post-Doctoral Fellowship, Department of Solar System Sciences, ISAS/JAXA, Japan.
E-mail: liang.yuying@ac.jaxa.jp.
† PhD Candidate, Department of Space and Astronautical Science, The Graduate University for Advanced Studies, SOKENDAI, Japan. E-mail: nishanth@ac.jaxa.jp.
‡ Professor, Department of Space Flight Systems, ISAS/JAXA, Japan. E-mail: kawakatsu.yasuhiro@jaxa.jp.
§ Professor, Department of Solar System Sciences, ISAS/JAXA, Japan. E-mail: fujimoto.masaki@jaxa.jp.

AAS 20-450

# SPACECRAFT BODY-FRAME HOVERING OVER AN ASTEROID USING A DIRECT ADAPTIVE CONTROL STRATEGY

Madhur Tiwari,* Troy Henderson,† and Richard J. Prazenica‡

In this paper, we have implemented a direct adaptive control strategy for the spacecraft hovering problem in the vicinity of an asteroid. The asteroid and spacecraft parameters, including gravitational parameters, solar radiation pressure, inertias and higher order harmonics, are assumed to be unknown. A fully nonlinear dynamical model with McCullagh's gravitational approximation and solar radiation pressure is implemented. Hovering trajectories are presented in an asteroid fixed body frame. Simulation results show successful trajectory tracking using the direct adaptive control strategy.

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* PhD Candidate, Embry-Riddle Aeronautical University, Department of Aerospace Engineering, Daytona Beach, Florida 32114, USA.

† Assistant Professor, Embry-Riddle Aeronautical University, Department of Aerospace Engineering, Daytona Beach, Florida 32114 USA.

‡ Associate Professor, Embry-Riddle Aeronautical University, Department of Aerospace Engineering, Daytona Beach, Florida 32114, USA.

# IMPROVING THE ACCURACY OF LANDER DEPLOYMENT TO ASTEROIDS BY SPIN RATE CONTROL

**Xiangyu Li,* Daniel J. Scheeres,† and Dong Qiao‡**

Deploying small landers to asteroid surface is an important way to increase the scientific return of asteroid rendezvous missions with less risk. But the deployment of a lander in a weak and perturbed gravity environment is a challenging task. The lander may rebound several times before it settles down, resulting in a large deviation from its first landing site. This paper proposes a novel method to increase the accuracy of ballistic deployment by spin rate control. Based on the contact dynamics of rigid bodies, the spin rate of a spherical lander is controlled before each impact to change its after-impact velocity so that it can be driven into a bouncing trajectory that makes it come back to its originally targeted on the surface. In that case, the lander can remain in the vicinity of its original landing site, as its velocity dissipates until it finally rests on the surface. First, the contact dynamics of a spherical lander is investigated. The analytical solution of the velocity change with the initial spin rate is derived. Then, the necessary condition of bouncing trajectories is investigated based on a spherical model. The influence of bouncing velocity, the spin rate of an asteroid and latitude of the landing site is discussed. Next, deployment trajectories suit-able for the proposed deployment method are studied with different surface parameters. Finally, the feasibility and robustness of the proposed method are verified on a polyhedron model of asteroid Bennu. It is found that the proposed deployment method can enable a precise landing if the surface environment is well-known and largely reduce the landing dispersion under an uncertain environment. This paper provides a novel idea for future asteroid lander deployment and surface exploration missions.

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* Postdoctoral Fellow, School of Aerospace Engineering, Beijing Institute of Technology, Beijing, 100081, China.
† Professor, Ann and H. J. Smead Aerospace Engineering Science Department, University of Colorado Boulder, CO 80309, USA.
‡ Professor, School of Aerospace Engineering, Beijing Institute of Technology, Beijing, 100081, China.

AAS 20-466

# SCIENCE ORBIT DESIGN FOR A DEIMOS MISSION

**Michael R. Thompson,[*] Mitchell W. Dominguez,[†] and David A. Spencer[‡]**

For a small satellite mission to Deimos, a close-proximity orbit is required to provide global high-resolution science observations. However, due to the small mass of Deimos, many close-proximity orbits are unstable. This paper explores the dynamics of the Deimos system, provides stability analyses for distant retrograde and quasi-satellite orbits, and explores coverage and resolution metrics for a number of stable Deimos science orbits and sensor parameters. A tool for exploring the orbital tradespace and resulting coverage metrics is used to provide potentially useful science orbits for a Deimos mission.

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[*] M.S. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA.
[†] Ph.D. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA.
[‡] Mission Manager, Mars Sample Return Campaign, Jet Propulsion Laboratory, Pasadena, CA 91109, USA.

**AAS 20-471**

# FEASIBILITY STUDY OF GATHERING MATERIAL FOR ISRU FROM AN ACTIVE COMET COMA

**Anivid Pedros Faura*** **and Jay W. McMahon†**

In this paper an estimate of the potential mass that can be obtained by orbiting an active comet is given. The main dynamic forces acting upon a spacecraft orbiting an active comet are modeled considering that during the trajectory part of the gas of the coma is captured and, therefore, a change in momentum and mass occurs. Different orbits are proposed and discussed for the particular case of comet 67P/Churyumov-Gerasimenko. The purpose of this paper is to show the feasibility of in situ resource utilization for on-orbit operations.

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* Graduate Student, Aerospace Engineering Sciences, University of Colorado Boulder, AIAA Member.
† Assistant Professor of Engineering, Department of Aerospace Engineering Sciences, University of Colorado, 429 UCB, Colorado Center for Astrodynamics Research, Boulder, CO 80303, USA. AIAA Member.

**AAS 20-494**

# ORBIT DESIGN TO MAXIMIZE INFORMATION FOR SPACECRAFT NAVIGATION AT ACTIVE COMETS

**Mark J. Moretto[*] and Jay McMahon[†]**

The orbital environment at an active comet is highly perturbed and non-linear due to strong perturbations from non-spherical gravity, solar radiation pressure, and coma drag, among other forces. Upon arrival at a "new" comet, an orbital mission must estimate the spacecraft's position, velocity, and a number of parameters related to the perturbing forces, such as the spherical harmonic coefficients of the gravity field and the spacecraft drag characteristics. Orbits must be designed to maintain spacecraft safety, specifically such that the spacecraft doesn't impact the comet and that enough information is gathered to sufficiently predict the spacecraft state during subsequent, presumably more daring, mission phases. This paper presents a consider covariance analysis using optical navigation images for various orbits about an active comet, showing how state uncertainty evolves along specific trajectories. Trajectories improving the state knowledge of specific parameters are discussed. Filter performance and convergence is discussed.

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[*] Graduate Student, Aerospace Engineering Sciences, University of Colorado Boulder, 442, 3775 Discovery Drive, Boulder, CO 80303, USA.

[†] Assistant Professor, Aerospace Engineering Sciences, University of Colorado Boulder, 461, 3775 Discovery Drive, Boulder, CO 80303, USA.

**AAS 20-504**

# AUTONOMOUS SELECTION OF SPACECRAFT LANDING LOCATION ON HAZARDOUS SMALL BODIES

**Joshua D. Nelson[*] and Hanspeter Schaub[†]**

In recent years, there has been a great deal of research and development pertaining to the autonomous landing of spacecraft on small bodies, such as asteroids. The capabilities to identify and avoid large rocks and other hazards on the surface of small bodies has seen significant improvement, however most modern techniques search for a location on the surface that contains no hazards within a scaled circular/elliptical footprint. A challenge with this approach is that such acceptable landing locations may be few and far between, or may not even exist at all, on asteroids with highly hazardous terrain. This paper proposes the use of a geometrically conforming footprint to significantly widen possible landing regions. A technique is formulated as the foundation for an autonomous landing location selection algorithm that utilizes such a footprint. This technique offers coarse and fine variations for determining a landing location, both with their own pros and cons. An algorithm that utilizes this technique is constructed, and preliminary test results are presented. These results highlight the differences between coarse and fine variations, and show the current state of the technique to have a 94:3% success rate. Finally, improvements and the future development of this technique are discussed.

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[*] Graduate Research Assistant, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO, 80309 USA. E-mail: Nelson.Joshua@colorado.edu.

[†] Glenn L. Murphy Chair of Engineering, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, 415 AERO, Colorado Center for Astrodynamics Research, Boulder, CO 80309, USA.

**AAS 20-517**

# MODELLING SIGNATURES OF INTERNAL DENSITY HETEROGENEITIES FOR ASTEROIDS GRAVITY FIELDS

**Natasha C. de Araujo,[*] Daniel J. Scheeres,[†] Evandro M. Rocco,[*] Marcelo L. Mota,[‡] and Walkiria Schulz[§]**

Generally, when we perform analysis for asteroids a constant density body is considered. However, from what we know from images and missions, especially fresh results obtained from OSIRIS-Rex, asteroids are bodies with different densities internally, including density concentrations due to boulders and possible regions of voids. With this in mind this work presents an application using the Finite Element Model (FEM) to explore gravity fields of small bodies considering internal density heterogeneities.

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[*] Space Mechanics and Control Division National Institute for Space Research Brazil (INPE), São José dos Campos, 12227-010, Brazil.
[†] Ann H.J. Smead Department of Aerospace Engineering Science, University of Colorado, Boulder, CO 80303, USA.
[‡] São Paulo Federal Institute of Education, Science and Technology (IFSP), Hortolândia, 13183 – 091, Brazil.
[§] Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, X5000JKP, Córdoba –, Argentina.

AAS 20-530

# TRAJECTORY DESIGN AND OPERATIONAL CHALLENGES FOR THE EXPLORATION OF PHOBOS

**Elisabet Canalias,* Laurence Lorda,* Hongru Chen,† and Hitoshi Ikeda‡**

Designing trajectories to allow for long observation campaigns of planetary moons is not an easy task. Quasi-Satellite Orbits are a type of distant retrograde orbits suitable for Phobos exploration missions, as they offer a convenient means to orbit this moon in the sense of relative motion. MMX (Martian Moons eXploration mission) is a chemical-propulsion sample return mission currently under development at the Japanese exploration agency (JAXA) which plans to make extensive use of QSO (Quasi Satellite Orbits) trajectories during its three-year stay in the vicinity of Phobos. Moreover, the French Space Agency (CNES) contributes to the mission analysis studies of MMX for the Phobos proximity phase in the frame of a larger collaboration between the Japanese and the French agencies, which also includes the delivery of a major payload (MIRS), as well as a rover built in collaboration with the German agency (DLR). Several of the major challenges that MMX teams have to face when building orbital scenarios exhibiting the best trade-off in terms of scientific return, maneuver cost and operational risk will be outlined in this paper. In particular, this work focuses on the contribution of the flight dynamics team at CNES to the design of three dimensional QSO trajectories and their operational use. An overview of the methods implemented to support the choice of suitable spatial trajectories around Phobos, in addition to the design of transfer trajectories, station-keeping and eclipse analyses for 3D-QSO will be presented.

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* CNES (French Space Agency), Department of Flight Dynamics. 18 Av. Edouard Belin, 31400, Toulouse (France).
† IMCCE, (Institut de Mécanique Céleste et calcul d'éphémérides), Observatoire de Paris, 77 avenue Denfert-Rochereau, 75014 Paris (France).
‡ JAXA (Japan Aerospace Exploration Agency), Research and development directorate, 3-Chome-1-1 Yoshinodai, Sagamihara (Japan).

**AAS 20-609**

# COUPLED ORBIT-ATTITUDE MOTION OF ASTEROID HOPPING ROVER BY CONSIDERING ROUGH TERRAINS

**Tongge Wen,[*] Ziwen Li,[†] Yonglong Zhang,[‡] Kyle T. Alfriend,[§] Yang Yu,[**] and Xiangyuan Zeng[††]**

This paper presents a numerical methodology to investigate the coupled orbit-attitude motion of a rover under the unilateral constraint of asteroid terrains. A newly rocky polyhedral model is generated by considering the complex surface terrains with rocks and boulders. The coupled attitude-orbit dynamics are discussed in terms of 6 DOF orbital, surface, and collision motion. The interaction between the rover and the rocky polyhedral model is performed by directly integrating the dynamical equations. To evaluate the effectiveness of the method, a hypothetical deployment case on the asteroid 101955 Bennu is carried out with its application to a spheroid rover. The influence of terrains is investigated by comparing the trajectories involving the original polyhedral model with the rocky model.

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[*] Graduate Student, School of Automation, Beijing Institute of Technology, Beijing 100081, China. E-mail: 3120180946@bit.edu.cn.

[†] Graduate Student, School of Automation, Beijing Institute of Technology, Beijing 100081, China. E-mail: 3220190709@bit.edu.cn. Member AAS.

[‡] Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China. E-mail: yonglong19@mails.tsinghua.edu.cn.

[§] Texas A&M Engineering Experiment Station Research Chair Professor, Department of Aerospace Engineering, College Station, Texas 77843, USA. E-mail: alfriend@aero.tamu.edu. Fellow AIAA.

[**] Associate Professor, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China. E-mail: yuyang.thu@icloud.com.

[††] Associate Professor, School of Automation, Beijing Institute of Technology, Beijing 100081, China. E-mail: zeng@bit.edu.cn (corresponding author). Member AIAA, Member AAS.

**AAS 20-617**

# IMAGE-BASED TRAJECTORY ESTIMATION OF AN ARTIFICIAL LANDMARK DEPLOYED BY HAYABUSA2

**Tetsuya Kusumoto,[*] Osamu Mori,[†] Shota Kikuchi,[‡] Yuki Takao,[‡] Naoko Ogawa,[‡] Takanao Saiki,[†] and Yuichi Tsuda[§]**

JAXA's Hayabusa2 is an asteroid sample return mission which achieved two landing operations. To realize autonomous navigation and guidance under uncertain terrain conditions, the spacecraft tracked artificial landmarks called target markers, which the spacecraft deployed towards the surface of the asteroid. We propose a method of estimating the trajectory of the Target Markers using only images and investigate the accuracy and reliability. To determine the relative attitude towards the asteroid surface, we propose an attitude estimation method by using the spacecraft's own shadow. This paper confirms that the estimated trajectory is sufficiently accurate and the proposed method is a viable option for future missions using artificial landmarks.

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[*] Graduate Student, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-0033. E-mail: kusumoto.tetsuya@ac.jaxa.jp.

[†] Assistant Professor, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-5210.

[‡] Researcher, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-5210.

[§] Professor, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-5210.

**AAS 20-622**

# MISSION ANALYSIS OF SPACE-BASED TELESCOPES TO DETECT IMPACTING NEAR-EARTH OBJECTS

**Olga Ramirez Torralba[*] and Jeannette Heiligers[†]**

Recognising the threat of near-Earth objects (NEOs) to life on Earth, many projects have been developed worldwide with the aim of detecting potential impactors, most of which are focused on ground-based surveys. However, ~20% of the Earth-threatening NEOs are estimated to be approaching Earth from the day-side, and are thus very difficult to detect using ground surveys. Over the last decade, several space-based capabilities have emerged in an effort to discover and catalogue NEOs in order to better quantify their risk of impact, yet little research has gone into dealing with imminent-impacting NEOs. The aim of this paper is to design a space mission that places a telescope in-orbit in order to detect and provide warning for Earth-impacting NEOs down to 20m in size, by determining the performance of both a visible and an infrared (IR) space-based telescope used in two mission candidates. The first mission candidate consists of a halo orbit about the artificial equilibrium point sub-$L_1$ of the Sun-Earth (SE) system, which is displaced with respect to the classical $L_1$ point, along the SE direction towards the Sun, through the use of solar-sail propulsion. As second mission candidate, three vertical Lyapunov orbits about the libration points $L_3$, $L_4$ and $L_5$ of the Sun-Venus system are considered. A trade-off between detection rates and warning times is conducted to determine the most suitable space-based NEO survey system. It is concluded that an IR space-based telescope placed at the SE solar-sail displaced $L_1$ point is the best option because of the long warning times obtained and the beneficial contribution to existing ground-based NEO surveys. A preliminary mission analysis is also performed to determine a solar-sail propelled transfer trajectory to the SE sub-$L_1$ region, assuming a ride-share launch on ESA's Euclid mission.

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[*] Master Student, Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS, Delft, The Netherlands.
[†] Assistant Professor, Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS, Delft, The Netherlands.

**AAS 20-627**

# CONCEPTUAL DESIGN FOR DEFLECTING POTENTIALLY HAZARDOUS ASTEROID BY SPACE DUSTER

**Ramil Santos,[*] Xu Ming,[†] Yaru Zheng,[‡] and Xingji He[§]**

The Deflecting Asteroid by Dusting (DAD) mission addresses the challenges of deflecting a potentially hazardous asteroid (PHA) that has a large probability of impacting Earth. It is an innovative and mass-minimalist approach to exploit PHAs by using the dusting deflection method. This conceptual design is developed based on an asteroid space duster, which is a space miner that is equipped with dust mining equipment, path-finding systems, and robotic capabilities, that converts available materials into mining prospects. It also stores energy to power the space miner and produces thrust to deflect the asteroid. The primary goals of DAD are to use the dust-to-thrust dusting technique on a PHA and to characterize and measure the deflection caused by the dusting. The 99942 Apophis is used as the reference asteroid in the dust-to-thrust study to test the feasibility of using the approach for deflecting PHAs. There are currently no methods that continuously use the dust-to-thrust approach from an asteroid mining perspective in comparison to the existing deflecting asteroid concepts. This unsolved problem is the focus of the DAD-related study.

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[*] Ph.D. Student, School of Astronautics, Beihang University, Beijing, 100191, China. E-mail: mengtefu@buaa.edu.cn.
[†] Associate Professor, School of Astronautics, Beihang University, Beijing, 100191, China.
E-mail: xuming@buaa.edu.cn.
[‡] Assistant Engineer, 9th Designing of China Aerospace Science and Industry Corp., Wuhan, 430040, China.
E-mail: zhengyaru@buaa.edu.cn.
[§] Ph.D. Student, School of Astronautics, Beihang University, Beijing, 100191, China. E-mail: hexingji@buaa.edu.cn.

AAS 20-628

# ASTEROID RENDEZVOUS MISSIONS WITH DEPARTURE FROM EARTH-SUN L4 AND L5

**Alessia De Iuliis,[*] Luigi Mascolo,[†] Stefano De Santi,[‡] and Lorenzo Casalino[§]**

The proposed paper considers CubeSats missions that start from the Earth-Sun triangular Lagrangian points L4 and L5 and have rendezvous with Near-Earth asteroids. CubeSats could be left at the departure point as a piggyback of a primary mission and start their own mission from this point. Departure from either L4 or L5 is favorable for missions to Near-Earth objects that have a close encounter with the Earth. With the use of electric propulsion, the spacecraft performs an Earth flyby about one or two years after departure, to move the CubeSat to the asteroid orbit and achieve rendezvous. An indirect optimization method is used to minimize propellant consumption. Results show the feasibility of this mission concept with the current technology for some cases, and the need for small improvements to enlarge the set of attainable targets.

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[*] Ph.D. Student, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy.

[†] Ph.D. Student, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy.

[‡] Undergraduate Student, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy.

[§] Professor, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy.

AAS 20-631

# A COVARIANCE STUDY FOR GRAVITY ESTIMATION OF BINARY ASTEROIDS

**Alex B. Davis[*] and Daniel J. Scheeres[†]**

In support of future missions to binary asteroids, such as the ESA HERA mission, we develop a covariance analysis framework for navigation of spacecraft about binary asteroid systems. Our dynamics model assumes the restricted full three body problem (RF3BP). The RF3BP is a dynamical model in which a massless spacecraft or particle orbits two arbitrary asymmetric mass distributions, in this case asteroids. Because of their irregular shapes, the gravitational effect of the asteroids on one another and the spacecraft are modelled using a Legendre polynomial expansion of their mass distribution; described by the inertia integrals of each body. Within this dynamical model we develop the state transition matrix (STM) for the full system state as well as the mass parameter sensitivity matrix (MPSM) which linearly maps uncertainty in the mass parameters into the full system state. With this tool set we perform a series of consider covariance analyses to better understand the estimation of the mass parameters of binary asteroid systems. We identify the influence of higher order mass parameters, error sources, and system excitement on the estimation uncertainty. Our study is performed for 65803 Didymos, the binary target of the DART and HERA missions.

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[*] PhD Candidate, Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discover Dr., Boulder, CO 80303, USA.
[†] Richard Seabass Chair Professor, Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discover Dr., Boulder, CO 80303, USA.

**AAS 20-661**

# SPACE CARVING IN SPACE: A VISUAL-SLAM APPROACH TO 3D SHAPE RECONSTRUCTION OF A SMALL CELESTIAL BODY

**Travis Driver,[*] Mehregan Dor,[†]**
**Katherine A. Skinner[‡] and Panagiotis Tsiotras[§]**

Missions to small bodies typically involve an initial characterization phase, where a 3D shape model is constructed for the purposes of vision-based relative navigation and estimation of the dynamical properties of the body. Current state-of-the-practice methods for shape reconstruction, such as Stereophotoclinometry (SPC), rely heavily on human-in-the-loop processes executed on the ground, thus constraining the level of autonomy that can be achieved by these missions. This work details a visual simultaneous localization and mapping (VSLAM) based autonomous shape reconstruction algorithm for the estimation of the dynamical properties and for the construction of a preliminary shape model of a small celestial body. The proposed method is applied to both simulated and real image data and is shown to accurately reconstruct the 3D shape of the target asteroid.

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[*] PhD Student, Institute for Robotics and Intelligent Machines, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30313, USA.
[†] PhD Candidate, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30313, USA.
[‡] Postdoctoral Fellow, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30313, USA.
[§] David and Lewis Chair, Professor, Institute for Robotics and Intelligent Machines, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30313, USA.

AAS 20-662

# ESTIMATING ASTEROID DENSITY DISTRIBUTION FROM GRAVITY MEASUREMENT WITH POSITION UNCERTAINTY

**Woosang Park*  and Suman Chakravorty†**

Densities of asteroid finite elements are estimated by the least-squares solution with the estimated positions and known gravity field. Numerical simulation results show that the proximity to an asteroid, position estimation accuracy, gravity accuracy, and the number of gravity-position data sets play a significant role in density estimation performance. Moreover, the proposed method achieves 76% matching success rates by using ten spacecraft in perturbed orbits around Kleopatra within 8.5 days. This paper provides insights on future asteroid density estimation missions using gravity measurements with position uncertainty.

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* Ph.D. Student, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
† Associate Professor, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.

AAS 20-676

# MASCON MODELS FOR ESTIMATING HETEROGENEOUS SMALL BODY DENSITY DISTRIBUTIONS

Patrick T. Wittick,* Ryan P. Russell,† Kenneth Getzandanner,‡ and Erwan Mazarico§

Layered, polydisperse mascon distributions are applied to provide fast and global external field representations and feasible models of internal small body density. Mascon models are divided into regions, the densities of which are estimated using the mission-derived coefficients of a reference spherical harmonics gravity field as measurements. The estimation algorithm is shown to recover simulated truth mascon models to high precision given suitable mascon and region geometry. An application for Comet 67P/C-G is presented, wherein the mascon configuration is varied and regional density values are estimated. The application of a constant-density prior with appropriately tuned weights enables the estimation algorithm to identify model solutions with positive-valued densities throughout. The Stokes coefficients of Pareto-optimal estimated mascon proxy models fall within one standard deviation of the Rosetta gravity solution in every case.

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* Graduate Research Assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin; currently Member of the Technical Staff, Flight Mechanics Department, The Aerospace Corporation, 2310 E El Segundo Blvd, El Segundo, CA 90245, USA.

† Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 2617 Wichita Street, C0600, Austin, TX 78712, USA.

‡ Flight Dynamics Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

§ Research Scientist, Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

AAS 20-710

# BENNU SHAPE MODEL VALIDATION METHODS AND RESULTS*

**Daniel P. Lubey,† Julie Bellerose,* Brian M. Kennedy,* Nickolaos Mastrodemos,‡ Brian Rush,* Dianna Velez,* Olivier S. Barnouin,§ Michael G. Daly,** Jeff A. Seabrook,§ and Dante S. Lauretta††**

The OSIRIS-REx Independent Shape Modeling Team, staffed by the Jet Propulsion Laboratory (JPL), has used stereophotoclinometry (SPC) to produce a three-dimensional shape model of Bennu. The SPC process is informed by (but is separate from) orbit determination, so it is important to ensure that the resulting shape model is consistent with all available spacecraft tracking data. Specifically, checking the shape model's consistency with LIDAR measurements can illuminate any discrepancies, because LIDAR measurements are highly correlated with the shape model. This study focuses on the JPL experience with these LIDAR measurements and the greater context of the shape model validation process.

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† Outer Planet Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
‡ Solar System Dynamics Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
§ Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA.
** York University, Toronto, ON, M3J 1P3, Canada.
†† Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

**AAS 20-725**

# A DATA-DRIVEN APPROACH TO PREDICT ΔV SENSITIVITY AND CORRECT PROPAGATION ERRORS OF NEAR-EARTH ASTEROIDS

**Sung Wook Paek,[*] Sivagaminathan Balasubramanian,[†] and Olivier L. de Weck[‡]**

A data-driven approach is presented in this paper to describe (1) the deflection sensitivity of asteroids and (2) its position error between the ground truth and an in-house propagator. It is shown that the proposed formulas are in fact extensions of Fourier series with coefficients that are power functions. The proposed formulas are validated against datasets from JPL Center for NEO Studies (CNEOS) and JPL HORIZONS.

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[*] Engineer, Simulation Group, Samsung SDI R&D Center, Gyeonggi-do 16678, Korea.
[†] Engineer, Simulation Group, Samsung SDI R&D Center, Gyeonggi-do 16678, Korea.
[‡] Professor, Aeronautics and Astronautics, Massachusetts Institute of Technology, MA 02139, USA.

AAS 20-728

# DEPLOYMENT OF SMALL-BODY LANDERS FROM TERMINATOR ORBITS IN PERTURBED ENVIRONMENTS

Daniel Villegas-Pinto,* Daniel Hestroffer,†
Elisabet Canalias,‡ and Francesco Capolupo§

In this paper, we analyze the deployment of landers from terminator orbits to small bodies in perturbed environments. In the frame of small-body exploration, landers have proven valuable assets due to the possibility of performing scientific operations directly on the surface of these bodies. Terminator orbits are great candidates for small-body exploration due to their robustness against gravitational uncertainties and solar radiation pressure (SRP), and for that a popular option for current and upcoming missions. In this study, we analyze the possibilities of deploying landers with different mass-to-area ratios from periodic terminator orbits close to the $L_2$ equilibrium point. We make use of the unstable manifolds of the orbits to design landing trajectories that could be used as foundations for future missions. These trajectories exploit the natural dynamics around the $L_2$ equilibrium point's unstable manifold, which intersects the secondary body for large enough ratios of SRP acceleration to gravity acceleration. Using an Augmented Hill Problem model, which includes SRP and eclipses, we apply this methodology to asteroids Bennu and Ryugu. We find that this approach leads to extremely robust and direct trajectories that land with velocities below the two-body escape velocity and at angles close to the surface normal. Although these trajectories can display long times of flight, we introduce the concept of manifold-derived trajectories, which, albeit not effectively manifold trajectories, can reduce the times of flight significantly to allow for a wider flexibility when designing a landing trajectory and maintain the advantages of the traditional manifold trajectories.

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* PhD Candidate at CNES / IMCCE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Univ., Univ. Lille, 77 av. Denfert-Rochereau, 75014 Paris, France. E-mail: daniel.villegas-pinto@obspm.fr.
† IMCCE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Univ., Univ. Lille, 77 av. Denfert-Rochereau, 75014 Paris, France.
‡ CNES, 18 Av. Edouard Belin, 31400 Toulouse, France.
§ Airbus Defence and Space, 31400 Toulouse, France.

**AAS 20-743**

# MISSION ANALYSIS AND TRAJECTORY DESIGN FOR NANOSAT SCIENTIFIC EXPLORATION AROUND BINARY SYSTEMS LEVERAGING THE DYNAMICAL ENVIRONMENT

**Andrea Capannolo,[*] Andrea Pasquale,[†] Margherita Piccinin,[‡] Stefano Silvestrini,[§] Giovanni Zanotti,[**] and Michèle Lavagna[††]**

The increasingly ambitious objectives of small bodies exploration pose several difficulties to missions design, requiring a precise development of safe and robust trajectories, to maximize the science return whilst mitigating the detrimental effect of environmental uncertainties. A dedicated scenario is required for asteroids binary systems, where the presence of two attractors aggravates the uncertainties' influence. In such scenario, the paper proposes a mission concept for binary systems exploration, with the final objective of defining a safe and effective strategy to characterize the bodies. Particular attention is posed to surface observation and coverage, assuming a suitable payload dedicated for the purpose.

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[*] Ph.D. Candidate, Dept. of Aerospace Science and Technology, Politecnico di Milano, Italy.
[†] Ph.D. Candidate, Dept. of Aerospace Science and Technology, Politecnico di Milano, Italy.
[‡] Ph.D. Candidate, Dept. of Aerospace Science and Technology, Politecnico di Milano, Italy.
[§] Ph.D. Candidate, Dept. of Aerospace Science and Technology, Politecnico di Milano, Italy.
[**] Ph.D. Candidate, Dept. of Aerospace Science and Technology, Politecnico di Milano, Italy.
[††] Full Professor, Dept. of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy.

**AAS 20-747**

# AUTONOMOUS SMALL BODY GRAVIMETRY VIA A2C PATH-PLANNING

**Manuel Indaco,[*] Michèle Lavagna,[†] and Davide Guzzetti[‡]**

The success of proximity operations near small bodies relies on proper characterization of the corresponding gravitational environment; the accuracy of the gravity field model is a critical element to plan safe spacecraft trajectories and constitutes a crucial aspect for the definition of the spacecraft dynamics. Currently, flight operations required for an accurate reconstruction of the gravity field are orchestrated by ground control personnel; however, automatizing such flight control processes may yield reduced operational costs and additional mission opportunities. The problem of autonomous gravity field reconstruction can be formulated as a Partially Observable Markov Decision Process; in this framework, a spacecraft moving in an unknown gravitational environment can be modeled as an agent that autonomously implements a guidance policy to obtain accurate gravimetric measurements. Possibly compatible with limited on-board resources, advances in flight autonomy may be sought through the exploitation of novel techniques based on Reinforcement Learning (RL) and Artificial Neural Networks (ANN). The architecture proposed in this work employs a Hopfield Neural Network (HNN) for the reconstruction of the gravity field, which is represented as a spherical harmonics expansion, assuming an Exterior Gravity Field Model. The agent's objective is to determine a trajectory around the target body that would allow the quick and precise estimation of the spherical harmonics coefficients via HNN. The algorithm adopted is the Advantage-Actor Critic (A2C), where the agent plays the roles of the Actor; such RL algorithm exploits two networks that work in parallel aiming to maximize the return, a scalar value that renders the accuracy of reconstruction of the gravity field. In particular, this works focuses on the reconstruction of the first zonal Stokes' coefficient $C_2$, testing the architecture on specific case studies, as well as on more generic environments. The ANN are updated using an Adam's algorithm for the learning process, which is driven by a reward function designed to retrieve the expansion coefficient in a quick and safe manner. Results presented in this paper show that an agent with proper training performs better than one that follows random behavior, achieving the desired accuracy more often than in a random policy simulation, in a wide pool of scenarios (different initial conditions for the same asteroid and different asteroid); in addition, gravity coefficient reconstruction performance are improved if an expert-knowledge is infused into the training process. Such results allow to assess the feasibility of the method proposed, thus defining a promising starting point for further developments.

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[*] Graduate Student, Department of Science and Aerospace Technology, Politecnico di Milano, Milano, Italy 20156.
[†] Professor, Department of Science and Aerospace Technology, Politecnico di Milano, Milano, Italy 20156.
[‡] Assistant Professor, Department of Aerospace Engineering, Auburn University, Auburn, AL 36849, USA.

# ORBITAL DEBRIS AND SPACE ENVIRONMENT

**AAS 20-460**

# OSAM-1 DECOMMISSIONING ORBIT DESIGN

**Michael A. Shoemaker,[*] Matthew Vavrina,[†] David E. Gaylor,[‡]**
**Richard McIntosh,[§] Michael Volle,[**] and Jeremy Jacobsohn[††]**

OSAM-1 is a NASA technology demonstration mission for several technologies associated with autonomous rendezvous and proximity operations, refueling, and on-orbit servicing, assembly and manufacturing. One unique aspect of this mission is the decommissioning orbit design that provides safe atmospheric disposal. The large spacecraft bus and internal fuel tanks necessitate a targeted reentry over the Pacific Ocean to minimize risk. The reentry orbit design must balance several requirements and constraints: reentry dispersions, minimum thruster shutoff altitude, thruster failure contingency, and orbit determination planning. We describe the process for simulating the decommissioning phase and show Monte Carlo dispersion results.

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[*] Aerospace Engineer, Navigation and Mission Design Branch (Code 595), NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
[†] Principal Systems Engineer, a.i. solutions, Inc., 4500 Forbes Blvd., Lanham, MD 20706, USA.
[‡] Aerospace Engineer, Navigation and Mission Design Branch (Code 595), NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
[§] Consulting Systems Engineer, a.i. solutions, Inc., 4500 Forbes Blvd., Lanham, MD 20706, USA.
[**] Principal Systems Engineer, a.i. solutions, Inc., 4500 Forbes Blvd., Lanham, MD 20706, USA.
[††] Chief Engineer, SAIC, 10210 Greenbelt Road Suite 450, Greenbelt, MD 20706, USA.

AAS 20-486

# SPACECRAFT SURVIVABILITY NEAR THE STABLE EARTH-MOON LAGRANGE POINTS

**Nathan R. Boone*[*] and Robert A. Bettinger[†]**

The theoretical analysis of the short- and long-term motion of natural space debris in the vicinity of the stable Earth-Moon Lagrange Points, $L_4$ and $L_5$, is presented with a focus on the potential debris risks to spacecraft operating near these points. Specifically, the research formulates a debris propagation model using four-body dynamics, then the applies a probabilistic survivability model to a notional spacecraft operating at the $L_4$ and $L_5$ Lagrange points to quantify the risks to the spacecraft from debris particles. The natural debris risks to spacecraft survivability are found to be incredibly low, but mitigation strategies to reduce the risk further are identified in this study. Overall, research into stable Lagrange point debris propagation enhances operational planning for Lagrange point space missions and understanding of the debris-related consequences of spacecraft mishaps near these points.

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[*] Graduate Student; Air Force Institute of Technology, Department of Aeronautics & Astronautics; 2950 Hobson Way, Wright-Patterson AFB, OH 45433, USA.
[†] PhD, Assistant Professor; Air Force Institute of Technology, Department of Aeronautics & Astronautics; 2950 Hobson Way, Wright-Patterson AFB, OH, 45433, USA.

# REAL-TIME THERMOSPHERIC DENSITY ESTIMATION VIA RADAR AND GPS TRACKING DATA ASSIMILATION

**David J. Gondelach[*] and Richard Linares[†]**

As the number of man-made Earth-orbiting objects increases, satellite operators need enhanced space traffic management capabilities to ensure safe space operations. For objects in Low-Earth orbit, orbit determination and prediction requires accurate estimates of the local thermospheric density. In previous work, the estimation of thermospheric densities using two-line element data and a reduced-order model for the upper atmosphere was demonstrated. In this paper we demonstrate an approach for density estimation using radar and GPS tracking data. We obtain improved density estimates using both radar and GPS data compared to empirical models. Using the GPS data of 10 satellites, we obtain density estimates with a daily 1-σ error of only 5% compared to 14% and 22% for empirical models and 10% for TLE-estimated density. These accurate density estimates can be used to improve orbit determination. In future work, we expect more accurate results if the tracking data of more objects with more diverse orbits is used.

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[*] Postdoctoral Associate, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. E-mail: dgondela@mit.edu.
[†] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. E-mail: linaresr@mit.edu.

**AAS 20-559**

# THE USE OF LONG SHORT-TERM MEMORY ARTIFICIAL NEURAL NETWORKS FOR THE GLOBAL PREDICTION OF ATMOSPHERIC DENSITY

**Taylor R. George[*] and Craig A. McLaughlin[†]**

The accuracy of the orbit determination process for satellites in low-Earth orbits, which affects the mission operations of such satellites, is limited by the accuracy of atmospheric density predictions. Artificial neural networks have been proven to be a valid method for atmospheric density prediction with accuracies meeting or, in most cases, exceeding the accuracies of atmospheric density models. However, previous research on the use of artificial neural networks for atmospheric density prediction has focused on localized, not global, predictions of atmospheric density. Thus, this research focused on the development of a global model for atmospheric density using artificial neural networks with long short-term memory (LSTM) units, trained and tested on data from the Challenging Minisatellite Payload (CHAMP) and the Gravity Recovery and Climate Experiment (GRACE). Overall, for higher solar and geomagnetic activity, the LSTM artificial neural networks were more accurate than NRLMSISE-00 and JB2008 more consistently when tested on shorter timespans. For lower solar and geomagnetic activity, the LSTM artificial neural networks were consistently more accurate than NRLMSISE-00 and JB2008, regardless of the length of the timespan for the testing data.

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[*] Graduate Student, Department of Aerospace Engineering, University of Kansas, Lawrence, KS, 66045, USA.
[†] Associate Professor, Department of Aerospace Engineering, University of Kansas, Lawrence, KS, 66045, USA.

AAS 20-626

# MODELING INTERNAL ENERGY DISSIPATION IN A TUMBLING DEFUNCT SATELLITE USING A FINITE ELEMENT METHOD

**Ryotaro Sakamoto* and Daniel J. Scheeres†**

A modeling method for studying the relationship between the internal energy dissipation of a tumbling defunct satellite and its overall de-tumbling is demonstrated. This approach uses a finite element method to model flexible body dynamics, including the effect of energy dissipation on the system rotational dynamics. An analysis model is developed which has rigid body components combined with flexible solar panels using finite element methods to capture the dynamic behavior of these combined components. The method models the full rotational dynamics of the system and feeds the resulting accelerations into the analysis models to form a closed system. By accounting for three-dimensional accelerations in the model, tumbling and fluctuation along flexible components is identified. The focus of this work is to explore interactions between the deformation of the satellite and spin rate change during tumbling. Although there are many physical factors that could cause internal energy dissipation, in this paper, the primary source is assumed to be deformation, thus modeling the likely state of a defunct satellite which has spent all of its propellant. The governing equations of motion are derived using rigid body principles and a damping equation. In the simulation, the inertia matrix is updated with the displacement of flexible appendages for each time step of the propagation. The characteristics of energy dissipation and spin rate transition caused by damping of the structure are explored using this model.

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* PhD Student, Aerospace Engineering Sciences, University of Colorado at Boulder, 3775 Discovery Drive, Boulder, Colorado 80303, USA.

† University of Colorado Distinguished Professor and the A. Richard Seebass Endowed Chair, Aerospace Engineering Sciences, 3775 Discovery Drive, Boulder, Colorado 80303, USA.

**AAS 20-629**

# CLEANING UP LOW EARTH ORBIT: DEORBIT ANALYSIS FOR AN ARTICULATING BOOM DRAG SAIL

**Jared D. Sikes,[*] William Ledbetter,[†] Rohan Sood,[‡]**
**Kamron Medina,[§] and Dana Turse[**]**

Safe navigation in the low Earth orbit environment is becoming increasingly threatened as the number of in-orbit spacecraft continues to grow. With the rising amount of orbital debris around Earth, the risk of impact with operational and defunct satellites significantly increases. In recent years, devices that augment the effective drag area of a satellite have been investigated to shorten a satellite's residual lifetime after mission operations are completed, removing it from the debris population. Drag sails will allow small satellites to operate in higher altitude orbits to perform science investigations previously unobtainable by satellites of this class, while still complying with international deorbit guidelines. Although drag sails seek to increase the decay rate through drag area augmentation, solar sails may be utilized to further speed up reentry by leveraging solar radiation pressure. Through the implementation of a semi-major axis decreasing control law, solar sails have been shown to be effective at reducing residual orbit lifetime. In some cases, the residual lifetime may be reduced by 70% compared to the drag-only scenario. A range of potential sail sizes are explored to identify trends in residual orbit lifetime, including averaging of deorbit start dates to account for variations in the exospheric temperature. Alongside the study of orbital lifetime, an analysis is performed to determine the feasibility of leveraging drag force for inclination change. While this technique is possible, leveraging solar radiation forces may provide a more robust means for achieving a desirable inclination change. Lastly, analysis is conducted to recognize the attitude stability of the spacecraft during sail operations. This research finding indicates that there exist key satellite attitude configurations and drag sail boom lengths that ensure a stable orientation when resistance to aerodynamic and gravity-gradient perturbations are considered.

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[*] Ph.D. Student, Astrodynamics and Space Research Laboratory, The University of Alabama, 401 7th Avenue Tuscaloosa, AL 35487, USA.
[†] Ph.D. Candidate, Astrodynamics and Space Research Laboratory, The University of Alabama, 401 7th Avenue Tuscaloosa, AL 35487, USA.
[‡] Assistant Professor, Astrodynamics and Space Research Laboratory, The University of Alabama, 401 7th Avenue Tuscaloosa, AL 35487, USA.
[§] Senior Mechanical Engineer, Roccor, 2602 Clover Basin Dr D, Longmont, CO 80503, USA.
[**] Director of Space Research and Development Programs, Roccor, 2602 Clover Basin Dr D, Longmont, CO 80503, USA.

**AAS 20-677**

# PRECISION ORBIT-DERIVED ATMOSPHERIC DENSITY USING HIGH FIDELITY GEOMETRY AND DRAG COEFFICIENT MODELING

**Craig A. McLaughlin[*] and Piyush M. Mehta[†]**

Precision orbit ephemerides (POE) are used as measurements to estimate atmospheric neutral density along the orbits of CHAMP and GRACE as part of an orbit estimation process. Previous work has relied on estimating ballistic coefficient, but for this work ballistic coefficients are calculated using detailed geometry, attitude, and drag coefficient models. The POE-derived densities are compared to accelerometer-derived densities in terms of root mean square error and cross correlation.

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[*] Associate Professor, Aerospace Engineering, University of Kansas, 1530 W. 15th St., Lawrence, KS 66045, USA.
[†] Assistant Professor, Department of Mechanical and Aerospace Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown WV 26506, USA.

AAS 20-703

# DEORBIT AND DEACTIVATION OF A GEO SATELLITE: TURKSAT-2A

Umit Cezmi Yilmaz,* Cemal Sakaci,† Mustafa D. Kocak,‡
Talha Er,§ and Baris Toktamis**

TURKSAT-2A was a GEO satellite, which has launched by Ariane in early 2001. Even, the expected orbital life was 12 years it had used up to end of 2016 in GEO. This paper, summarizes the whole de-orbit preparations and activities done on the satellite. All of the operations performed as planned, without any anomaly. After reaching the graveyard orbit, the satellite was passivated successfully. The motivation of this paper is to give some guidelines for foreseen de-orbit operations for a GEO satellite.

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* OOC Manager, TURKSAT Satellite Control Center, Ankara, Turkey. E-mail: cyilmaz@turksat.com.tr.
† OOC Engineer, TURKSAT Satellite Control Center, Ankara, Turkey. E-mail: csakaci@turksat.com.tr.
‡ OOC Engineer, TURKSAT Satellite Control Center, Ankara, Turkey. E-mail: mkocak@turksat.com.tr.
§ OOC Engineer, TURKSAT Satellite Control Center, Ankara, Turkey. E-mail: ter@turksat.com.tr.
** OOC Engineer, TURKSAT Satellite Control Center, Ankara, Turkey. E-mail: btoktamis@turksat.com.tr.

**AAS 20-711**

# COMPRESSED SENSING FOR SATELLITE CHARACTERIZATION

**Daigo Kobayashi[*] and Carolin Frueh[†]**

Characterization of space objects around the Earth is an essential step in space situational awareness. However, direct resolved imaging is rarely possible because of the large distances between a sensor and an object. This research discusses a potential application of a compressed sensing technique to characterize an unknown stabilized satellite in a known orbit from its non-resolved light curve. Compressed sensing was originally developed for efficient signal compression and reconstruction. In this paper, simulations showed that compressed sensing is capable of reconstructing resolved satellite images based solely on non-resolved light curves, assuming a reference observation is available to estimate the so-called sensing matrix. This result implies the great potential of compressed sensing in characterizing space objects.

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[*] Research Assistant, School of Aeronautics and Astronautics Engineering, Purdue University, West Lafayette, IN 47907-2045, USA. E-mail: dkobayas@purdue.edu.
[†] Associate Professor, School of Aeronautics and Astronautics Engineering, Purdue University, West Lafayette, IN 47907-2045, USA. E-mail: cfrueh@purdue.edu.

**AAS 20-721**

# SIMPLE MANEUVER CHARACTERIZATION WITH MACHINE LEARNING

**Rochelle Mellish**[*]

There are a number of orbital debris removal techniques that developed in response to the threat of on-orbit collisions between debris and functional space assets. Debris mitigation routines may be strengthened by maneuver characterization, which allows operators to make predictions about the future behavior of tracked space objects. In this work, resident space object motion histories are used to characterize the basic maneuvers of x-, y-, and z-directional rocket thrusts in the satellite body frame. Features are extracted from the time histories and used to group responses based on similarity. Several clustering techniques are compared for accuracy, with two supervised clustering methods showing promise for accurately characterizing new observations.

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[*] Sr. Professional Staff I, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA.

AAS 20-773

# EXTREMAL ORBIT TRANSFER CONTROL SOLUTIONS FOR TRAJECTORY SYNTHESIS USING THREE INTERMEDIATE THRUST ARCS IN A NEWTONIAN FIELD

**Dylan N. Morrison-Fogel[*] and Dilmurat M. Azimov[†]**

Analytical control and guidance solutions for extremal transfers between coplanar elliptical orbits in a Newtonian field are presented in the context of Mayer's variational problem. This problem is considered for one, two, and three intermediate thrust arcs. However, the studies show that the unique control solutions for an extremal transfer between arbitrary initial and final orbits require the use of three intermediate thrust arcs. Solutions to the continuity equations at the junction points for the trajectories containing these arcs are presented. It is shown that not all initial and final orbit conditions permit a third intermediate thrust arc which satisfies all continuity conditions at the junctions. Preliminary findings which satisfy junction conditions are found to be of comparable fuel efficiency to similar trajectories using only one or two IT arcs. Corresponding guidance laws are formulated in terms of thrust angle and mass-flow rate. Illustrative examples are presented.

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[*] Research Assistant, Department of Mechanical Engineering, University of Hawaii at Mãnoa, 2500 Campus Rd, Honolulu, HI 96822, USA.
[†] Associate Professor, Department of Mechanical Engineering, University of Hawaii at Mãnoa, 2500 Campus Rd, Honolulu, HI 96822, USA.

# SPACE SITUATIONAL AWARENESS, CONJUNCTION ANALYSIS AND COLLISION AVOIDANCE

AAS 20-423

# IMPACT OF SPACE WEATHER DRIVER FORECAST UNCERTAINTY ON DRAG AND ORBIT PREDICTION

Richard J. Licata,* Piyush M. Mehta,† and W. Kent Tobiska‡

SpaceWeather (SW) has a strong influence on satellite tracking, orbital decay, and collision avoidance in low Earth orbit (LEO). E.g., Satellite position Probability Density Functions (PDFs) essential for probability of collision, Pc, estimates are heavily dependent on drag. We have recently characterized the performance of SW driver forecast models used in operations by the US Air Force Space Command (AFSPC) with the High Accuracy Satellite Drag Model (HASDM). In this paper, we quantify the impact of SW driver forecast uncertainty on drag and orbit prediction.

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* Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, WV 26506-6106, USA.

† Assistant Professor, Department of Mechanical and Aerospace Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, WV 26506-6106, USA.

‡ President / Chief Scientist, Space Environment Technologies, Pacific Palisades, California, USA.

# HISTORICAL AND REAL-TIME GEO SATELLITE MANEUVER DETECTION ALGORITHM

**Jeffery B. Russell[*] and Katie McConky[†]**

As the GEO belt gets more cluttered with public and private interests, having Space Situational Awareness (SSA) is critical. When examining satellite patterns of life(POL), detecting maneuvers is necessary. With the wide variety of GEO satellites, capturing the movements using traditional algorithms in an automated fashion is not practical. We propose a novel algorithm that detects GEO slot-relocations by leveraging historical data, time-series segmentation algorithms, and propagated states. The developed algorithm produced a 95.4% recall rate on maneuvers after testing it on seventy-four random geostationary satellites.

[View Full Paper]

[*] Research Assistant, Department of Computer Science, Rochester Institute of Technology, Rochester, NY 14623, USA.
[†] Assistant Professor, Industrial and Systems Engineering, Rochester Institute of Technology, Rochester, NY 14623, USA.

**AAS 20-518**

# ASSOCIATION OF TOO SHORT ARCS USING ADMISSIBLE REGION

**Surabhi Bhadauria[*] and Carolin Frueh[†]**

The near-Earth space is filled with over 300,000 artificial debris objects with a diameter larger than one cm. For objects in Geosynchronous Earth Orbit (GEO) and Medium Earth Orbit (MEO) region, the observations are made mainly through optical sensors. These sensors take observations over a short time which cover only a negligible part of the object's orbit and are combined to form a Too Short Arc (TSA). Two or more such TSAs that belong to the same object are required for its initial orbit determination. Previous research proposed correlation techniques based on mapping of virtual debris objects generated from admissible regions of observations in orbital element space. To solve this correlation problem, a probabilistic approach based on finding the overlap between the admissible regions of TSAs is developed. In order to quantify the overlap, a Gaussian Mixture Model (GMM) representation is used in combination with Kullback-Leibler divergence approximation.

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[*] Graduate Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907-2045, USA.
[†] Associate Professor, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907-2045, USA.

AAS 20-551

# MULTI-STAGE ASTROMETRIC IMAGE PROCESSING USING STELLAR FEEDBACK

**Brad Sease,[*] Christopher Dapkus,[†] Charles Poole,[‡] Jose Rosales,[§] and Megan Johnson[**]**

Typical image processing for astrometric applications follows a multi-stage process including denoising, object extraction, and star catalog correlation. The final correlation stage is critical since an astrometric position for any non-star object derives from its position relative to the observed stars. Low or sparse stellar observations can produce poor astrometric solutions. To mitigate this problem, we develop an approach that combines the output of the base astrometric process with high-quality, complete star catalogs to increase the count of detected stars. We detail this stellar feedback approach and compare the resulting astrometric accuracy with a typical approach using real data.

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[*] Engineer, Computational Physics, Inc., Springfield VA 22151, USA.
[†] Engineer, Computational Physics, Inc., Springfield, VA 22151, USA.
[‡] Chief Systems Engineer, Computational Physics, Inc., Springfield, VA 22151, USA.
[§] Senior Systems Engineer, Computational Physics, Inc., Springfield, VA 22151, USA.
[**] Astronomer, United States Naval Observatory, Washington, DC 20392, USA.

**AAS 20-639**

# THE TIME FOR A SET OF TRAFFIC RULES HAS ARRIVED

**Ryan W. Shepperd[*] and Kristina C. DiOrio[†]**

Coordination between satellite operators has become burdensome as launch rates increase, constellations grow, and autonomous maneuvering satellites are put into operation. To reduce communication among operators, Iridium® proposes a set of traffic rules to determine the best course of action to reduce the probability of a collision. The set of traffic rules between maneuverable satellites will be unambiguously defined from a shared Conjunction Data Message. The proposed set of rules are outlined, and their cost evaluated using the Iridium constellation's experience at the altitude of the current peak encounter rate.

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[*] Member of the Technical Staff, Mission Planning and Orbital Analysis, Iridium Communications Inc, 44330 Woodridge Pkwy, Leesburg, VA 20176, USA.

[†] Senior Engineer, Mission Planning and Orbital Analyst, Iridium Communications Inc, 44330 Woodridge Pkwy, Leesburg VA 20176, USA.

AAS 20-681

# COVARIANCE BASED TRACK ASSOCIATION WITH MODIFIED EQUINOCTIAL ELEMENTS

**Paul J. Hughes*  and Kyle T. Alfriend†**

A modified set of equinoctial elements using the mean longitude and mean motion instead of the true longitude and semi-major axis are investigated for use in covariance based track association. With these elements the first variational equations are linear for the two-body problem, which means the nonlinearities in the covariance propagation only occur in the perturbations. This means the covariance should remain Gaussian longer. Also investigated are the use of mean elements and osculating elements for covariance propagation.

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* Graduate Research Assistant, Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, TX 77843-3141, USA.

† TEES Eminent Professor of Aerospace Engineering, University Distinguished Professor, 3141 TAMU, College Station, TX 77843-3141, USA.

AAS 20-714

# ELEVATION CONSTRAINT VERSUS PROBABILITY OF DETECTION IN AN OPTICAL SENSOR NETWORK DESIGNED FOR COMPLETE GEO COVERAGE

**Michael J. Rose* and Carolin E. Frueh†**

The general method of maintaining and updating resident space objects is by making observations from ground-based sensors, with geosynchronous Earth-orbiting objects being primarily detected and tracked optically. As the number of objects increases, there needs to be an effective sensor tasking strategy in place coordinating multiple optical sensors. Sensor networks that cover the whole geosynchronous object catalog in a single night are advantageous as they allow for full surveillance. In sensor tasking, often heuristic minimum local horizon elevation constraints are employed to avoid observation attempts that yield little return as the air-mass the reflected light from a space object passes through increases significantly with increasing zenith angle. In this paper, heuristic elevation constraints are compared to using tasking based on rigorously defined probability of detection. The results are shown in a realistic 34 sensor setup using the Two Line Element catalog. Limitations on the complete coverage in a single night of such a sensor network are shown.

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* Graduate Student, School of Aeronautics and Astronautics, Purdue University, 617 New York St., Lafayette, IN 47901, USA.

† Associate Professor, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave., West Lafayette, IN 47907, USA.

# AAS 20-752

# EARLY COLLISION AND FRAGMENTATION DETECTION USING ADMISSIBLE REGIONS

**Shahzad Virani[*] and Marcus J. Holzinger[†]**

This paper leverages the theory of admissible regions and numerical continuation to detect early collision and fragmentation events from uncorrelated tracks (UCTs) without orbit determination. Specifically, the problem looks at determining if two UCTs observed at two different times were generated from a collision or a fragmentation event. Given the measurements from UCTs, two admissible regions are created by enforcing energy, eccentricity, and periapsis radius constraint. Candidate space objects involved in a collision/fragmentation event must have identical position vector at the hypothesized fragmentation time. This puts a 3-dimensional constraint on the solutions space. However, since there are 4 unknowns, namely the range and range rate from two different admissible regions, the solution space becomes a 1-dimensional manifold. On this 1-dimensional manifold in R4 lies all possible range and range rates for the two observed UCTs that would result in a collision. At the hypothesized fragmentation time, space objects passing through this 1-dimensional manifold when mapped to the position space (R3) would become candidates for the objects involved in collision/fragmentation event. The proposed method is demonstrated on examples from objects in LEO and GEO.

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[*] Graduate Student, NDSEG Fellow, Aerospace Engineering Sciences Department, University of Colorado – Boulder, CO 80303, USA.

[†] Associate Professor, Aerospace Engineering Sciences Department, University of Colorado – Boulder, CO 80303, USA.

# DATA-DRIVEN ANOMALY DETECTION FOR RESIDENT SPACE OBJECTS USING AUTOENCODER WITH BINARY CLASSIFICATION

**Yiran Wang,[*] Hao Peng,[†] Xiaoli Bai,[‡] Genshe Chen,[§] Dan Shen,[**] and Erik Blasch[††]**

To detect anomaly for RSOs accurately and timely is critical to protect the long-term sustainability of space activities, including Space Situational Awareness (SSA) and Space Traffic Management (STM). In this paper, we explore a new data-driven framework based on deep autoencoder for RSOs' anomaly detection. A novel two-input autoencoder model is proposed to identify whether the tracks belong to the same orbit or not. An in-house simulation-based space catalog environment is used for experiments and analysis. We compare the proposed model with Principal Component Analysis (PCA) method in classification and the results show that the proposed method achieves higher accuracy in identifying whether two tracks are from the same orbits or not than the classical PCA method. Furthermore, the proposed method is also robust to noise data with high accuracy.

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[*] Graduate Student, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ, 08854, USA. E-mail: yw619@rutgers.edu.

[†] Postdoctoral Associate, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ, 08854, USA. E-mail: Astro.H.Peng@gmail.com.

[‡] Associate Professor, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ, 08854, USA. E-mail: xiaoli.bai@rutgers.edu.

[§] Intelligent Fusion Technology, Inc., 20271 Goldenrod Labe, Germantown, MD 20876, USA.

[**] Intelligent Fusion Technology, Inc., 20271 Goldenrod Labe, Germantown, MD 20876, USA.

[††] Air Force Office of Scientific Research (AFOSR), Arlington, VA 22203, USA.

AAS 20-766

# MCMC SAMPLING AND CLUSTERING METHODS FOR A RANDOMIZED-FINITE SET STATISTICS TECHNIQUE (R-FISST II)

**W. R. Faber,* U. R. Mishra,† S. Chakravorty,‡ and I. I. Hussein§**

This paper presents a novel approach to keeping the Random Finite Set (RFS) based Bayesian recursions tractable. We propose a randomized scheme using a Metropolis-Hastings, Markov Chain Monte Carlo (MCMC), based technique and Finite Set Statistics (FISST), termed Randomized FISST II (R-FISST II). This technique samples highly probable target-observation association hypotheses and uses them to approximate the posterior RFS based multi-object Probability Density Function (PDF). We compare and contrast this method with a Multi target tracking method based on R-FISST which is another related MCMC based technique. Next we look at the suggested kosher MCMC i.e. R-FISST II's sampled hypotheses to demonstrate the utility of clustering in hypotheses space instead selecting the top hypotheses for future propagation. We extend this idea of clustering to sequential processing of measurements. We show clustering for varying size multi-target PDFs using an intuitive Hellinger distance based measure. Finally, we demonstrate the performances of these clustering methods for a multiple space object tracking problem.

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* Research Scientist, L3 Applied Defense Solutions, 10807 New Allegiance Drive, Suite 401, Colorado Springs, CO 80921, USA.
† GRA, Department of Aerospace Engineering, TAMU, 575 Ross St, Room 301-A, College Station, TX 77843, USA.
‡ Associate Professor, Department of Aerospace Engineering, TAMU, 701 H.R. Bright Bldg., College Station, TX 77843, USA.
§ Applied Defense Solutions, 10440 Little Patuxent Parkway, Suite 600, Columbia, MD 21044, USA.

# ATMOSPHERIC RE-ENTRY GUIDANCE AND CONTROL

# CLOSED-FORM TRAJECTORY SOLUTION FOR SHALLOW, HIGH-ALTITUDE ATMOSPHERIC FLIGHT

**Giusy Falcone[*] and Zachary R. Putnam[†]**

A closed-form approximate solution for shallow, high-altitude atmospheric flight, consistent with aerobraking passes is proposed. The solution includes expressions for velocity, flight-path angle, and altitude for lifting, high-speed atmospheric flight, which can be used to quickly evaluate trajectories. The complete derivation of the solution is presented. The solution is based on the assumptions of small flight-path angles and altitude rate changing linearly with respect to time. Results show a good match between the proposed approximate solution and numerical integration of the full equations of motion for a variety of trajectory parameters, including vacuum periapsis altitudes, initial flight-path angles and velocities, and vehicle aerodynamic coefficients. Larger, but bounded errors are present in predicted atmospheric exit velocities. Generally, results show that the predicted final velocity has a maximum error of approximately 0.6% in nominal conditions where the assumptions hold. Exit velocity errors are lower for trajectories that dissipate less energy during atmospheric flight. Finally, a Monte Carlo simulation is used to show how errors in altitude, flight-path angle, and velocity remain bounded in the presence of perturbations. Overall, results indicate that the proposed approximate solution can be used for first-order fast trajectory design for aerobraking and other grazing atmospheric trajectories.

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[*] Ph.D. Student, Aerospace Engineering, University of Illinois at Urbana-Champaign, 104 S Wright St., Urbana, IL 61801, USA.

[†] Assistant Professor, Aerospace Engineering, University of Illinois at Urbana-Champaign, 104 S Wright St., Urbana, IL 61801, USA.

**AAS 20-485**

# APPLICATION OF GAUSSIAN MIXTURE MODELS FOR NONLINEAR UNCERTAINTY PROPAGATION DURING MARTIAN AEROCAPTURE

**M. J. Grace* and Jay McMahon†**

Aerocapture dynamics are highly nonlinear due to the nature of the drag accelerations a spacecraft in low atmosphere experiences, and result in highly non-Gaussian state distributions over short periods of time. While traditional nonlinear uncertainty propagation techniques such as the Unscented Transform (UT) and Scaled Unscented Transform (SUT) are widely used for capturing the mean and covariance of a nonlinearly propagated distribution, they break down when dynamics are highly nonlinear.[1, 2] Thus, alternative means of propagating uncertainty are required. Due to their ease of use, ability to be fully defined by their means and covariances, and compatibility with the UT and SUT, Gaussian Mixture Models[3] (GMMs) would be ideal for uncertainty propagation in aerocapture. This paper demonstrates where the UT and SUT breakdown in the aerocapture problem, while investigating the performance of propagating mixtures through atmospheric entry. Further, a state-of-the-art mixture-based technique known as the Adaptive Entropy Gaussian-mixture Information Synthesis method (AEGIS)[4] is applied to the aerocapture problem and its performance is assessed. It is found that GMMs initialized both manually and using AEGIS tend to capture the curvature of state distributions during aerocapture well, while providing better approximations of mean and covariance than a single Gaussian propagated by the UT and SUT.

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* Ph.D. Student, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder, CO 80303, USA.

† Assistant Professor, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder, CO 80303, USA.

**AAS 20-566**

# MULTI-EVENT DRAG MODULATION AEROCAPTURE GUIDANCE UNDER UNCERTAINTY

**Evan Roelke,[*] Jay W. McMahon,[†] and Philip D. Hattis[‡]**

While single-event, drag-modulated aerocapture control architectures have gained significant traction in the past decade due to their straightforward nature compared to lift modulation designs, they are left uncontrollable, and therefore prone to error accumulation, post-jettison. Multiple jettison events have been shown to improve on the single-stage designs, but still suffer from the uni-directional control capabilities of drag skirt jettison. Two new multi-event jettison guidance architectures are proposed in this paper: a conditional jettison method and a biased jettison method. These methods are compared against the state-of-the-art for two jettison events, considering both 400 km and 2000 km apoapsis altitude targets. The conditional jettison method is shown to mostly perform similarly to the state-of-the-art; however, its inconsistent performance is a significant drawback. The biased jettison method is shown to provide noticeable improvement to the state-of-the-art. Smaller first jettison event control ratios were shown to provide the largest improvement for the biasing method. The apoapsis altitude target and first stage biasing value were both shown to impact the relative performance benefit.

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[*] Draper Laboratory Fellow, The Charles Stark Draper Laboratory, Inc. Graduate Research Assistant, Orbital Research Cluster for Celestial Applications (ORCCA) Lab, Colorado Center for Astrodynamics Research, 1111 Engineering Drive, Boulder, CO 80309, USA.

[†] Assistant Professor, Orbital Research Cluster for Celestial Applications (ORCCA), Colorado Center for Astrodynamics Research, 1111 Engineering Drive, Boulder, CO 80309, USA.

[‡] Laboratory Technical Staff, The Charles Stark Draper Laboratory Inc., 555 Technology Square, Cambridge, MA 02139, USA.

**AAS 20-573**

# CONJUGATE-UNSCENTED-TRANSFORM-BASED APPROACH TO UNCERTAINTY ANALYSIS FOR TITAN ENTRY, DESCENT AND LANDING

**Kendra Hale,[*] Zach Hall,[†] and Puneet Singla[‡]**

The main objective of this paper is to outline a method that efficiently and accurately quantifies uncertainty in various quantities of interest during the entry, descent, and landing phase of a hypothetical Titan surface mission. A non-product, higher order numerical integration technique known as Conjugate Unscented Transformation (CUT) is utilized for this purpose. The CUT method is used to compute a polynomial surrogate model which can accurately replicate trade-off studies conducted through conventional Monte-Carlo analysis while drastically reducing computational burden associated with such traditional methods. Numerical simulations are presented and discussed which validate and demonstrate the utility of the presented approach.

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[*] Undergraduate Student in Penn State University's Department of Aerospace Engineering, State College PA, 16802, USA. E-mail: klh5881@psu.edu.

[†] Graduate Student in Penn State University's Department of Aerospace Engineering, State College PA, 16802, USA. E-mail: zyh5059@psu.edu.

[‡] Associate Professor, Department of Aerospace Engineering, Pennsylvania State University, State College, PA, 16802, USA. E-mail: psingla@psu.edu. AIAA Associate Fellow, AAS Fellow.

AAS 20-578

# NONLINEAR STATE ESTIMATION OF REENTRY VEHICLE USING POLYNOMIAL CHAOS-BASED ENSEMBLE FILTERING

Rajnish Bhusal* and Kamesh Subbarao†

In this paper, a novel framework is proposed to estimate the states and uncertain parameters of a nonlinear stochastic dynamical system. The nonlinear estimation problem is solved in a prediction-correction fashion. The initial uncertainties in states and parameters are propagated using generalized polynomial chaos expansion technique to compute the predicted estimates of states and parameters. In addition, a nonlinear estimator is developed to update the predicted estimates upon arrival of the measurements in ensemble filtering framework. The methodology is then applied to estimate the states and uncertain parameters of a hypersonic vehicle entering the Martian atmosphere. Numerical results show that the proposed filter outperforms the particle filter in terms of accuracy and computational efficiency.

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* Graduate Student, Mechanical and Aerospace Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA.
† Professor, Mechanical and Aerospace Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA.

AAS 20-595

# MARS EDL AND AEROCAPTURE GUIDANCE UNDER DYNAMIC UNCERTAINTY

**Davide Amato,* Shayna Hume,† Melis J. Grace,†
Evan Roelke,‡ and Jay W. McMahon§**

Future Mars exploration missions require groundbreaking advances in guidance for Entry, Descent, and Landing (EDL) and aerocapture in the highly uncertain Martian atmospheric environment. Existing guidance algorithms mitigate uncertainties by recomputing and correcting controls at high frequency during the descent; however, this approach does not produce optimal solutions under perturbations and is therefore not robust. This paper gives an overview of robust EDL and aerocapture guidance methods aimed towards the explicit minimization of dynamic uncertainty. We present a stochastic retargeting algorithm that corrects the nominal solutions generated by state-of-the-art guidance to minimize the mean error of the probability density function (pdf) at landing. In addition, we abate errors in the dynamical model used by Numerical Predictor-Correctors (NPCs) by predicting complex atmospheric profiles through both shallow and deep neural networks. We use efficient uncertainty quantification methods to conduct a preliminary analysis of aerocapture probability given initial state uncertainties, and outline a novel NPC algorithm for discrete-event drag-modulation guidance.

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* Postdoctoral Associate, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder 80303, CO, USA.

† Ph.D. Student, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder 80303, CO, USA.

‡ Draper Laboratory Fellow, The Charles Stark Draper Laboratory, Inc. Ph.D. Candidate, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder 80303, CO, USA.

§ Assistant Professor, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder, CO 80303, USA.

AAS 20-636

# MODELING RE-ENTRY BREAK-UP UNCERTAINTIES WITH CONTINUITY EQUATION AND GAUSSIAN MIXTURE MODELS INTERPOLATION

Mirko Trisolini[*] and Camilla Colombo[†]

The effect of uncertainties in the re-entry and break-up of satellites is analyzed. Two contributions are considered: the effect of the initial uncertainties of the parent trajectory and the break-up event, characterized by high thermal and mechanical loads and tumbling motion. Specifically, this last phenomenon may cause the scattering of the components off the nominal trajectory of the parent spacecraft. The presented study describes the uncertainties and the break-up event through probability distributions, propagates them using a continuum approach, and reconstructs the uncertainties at future states using the Starling suite developed at Politecnico di Milano.

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[*] Post-Doctoral Researcher, Dipartimento di scienze e tecnologie aerospaziali, Politecnico di Milano, via La Masa 34, 10156, Milano, Italy.

[†] Associate Professor, Dipartimento di scienze e tecnologie aerospaziali, Politecnico di Milano, via La Masa 34, 10156, Milano, Italy.

AAS 20-664

# ENTRY GUIDANCE FOR PROPELLANT OPTIMAL POWERED DESCENT IGNITION ON MARS

Connor D. Noyes* and Kenneth D. Mease†

Powered descent plays an important role in current Mars entry, descent, and landing operations, and its importance will only grow as future missions begin to utilize supersonic retropropulsion to deliver heavier payloads to the surface with pinpoint accuracy. In current Mars entry trajectories, bank angle modulation provides range control prior to parachute deployment. Our approach represents a paradigm shift in which the entry guidance objective is to deliver the vehicle to propellant-optimal ignition conditions for a chosen powered descent guidance. The powered descent guidance is used to define a target set, and a mapping from that target set to the propellant required for pinpoint landing. The proposed entry guidance uses this target, which allows us to explicitly coordinate the entry guidance with powered descent guidance, and propellant savings can be realized relative to traditional entry guidance. The approach is tested in a 1000 sample Monte Carlo simulation.

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* Ph.D. Candidate, Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA 92697, USA.

† Professor Emeritus, Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA 92697, USA.

AAS 20-688

# ROBUST OPTIMAL TRAJECTORY DESIGN AND GUIDANCE FOR PLANETARY AEROCAPTURE

**Casey R. Heidrich* and Marcus J. Holzinger†**

Hypersonic entry flight represents a challenging mission phase of any space vehicle designed to pierce the atmosphere of a planet. For many aeroassist applications, such as aerocapture, precise trajectory maintenance is required to meet mission criteria and ensure survival in extreme entry environments. Historically, entry guidance algorithms have operated on deterministic assumptions, where quantities describing the motion of the system are assumed exactly known. In reality, sparse model data and incomplete state knowledge introduce aleatory-epistemic uncertainty, which in turn degrade guidance prediction accuracy. This paper demonstrates a method for uncertainty mitigation in hypersonic entry flight through robust optimal control principles. An expectancy robustness measure is introduced to account for uncertain states and parameters. The optimal control problem is simplified to a more tractable form for rapid solution using a parametric control solution. The method is a natural extension to state-of-the-art guidance strategies built on bang-bang deterministic optimal control solutions. Results are applied to a Neptune aerocapture concept study and shown to improve dispersed performance in a semi-major axis orbit targeting problem.

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* Graduate Researcher, Ann & HJ Smead Aerospace Engineering Sciences, University of Colorado Boulder, 80309, USA.
† Associate Professor, Ann & HJ Smead Aerospace Engineering Sciences, University of Colorado Boulder, 80309, USA.

AAS 20-718

# AERODROP: PROSPECTS AND CHALLENGES FOR CO-DELIVERY OF PROBE AND ORBITER VIA AEROCAPTURE

Samuel W. Albert,* Robert D. Braun,† and Hanspeter Schaub‡

AeroDrop is a new way to include ride-along probes or orbiters on interplanetary missions, made possible by the advent of small satellites as secondaries for space science missions combined with the maturation of aerocapture technologies. This mission architecture involves the design of a probe with the aerodynamic characteristics to reach the surface from the same entry state as the mothercraft performing aerocapture – or vice-versa. By eliminating the need for an in-space divert maneuver, AeroDrop lowers the additional risk of these secondary smallsats. This study summarizes the key prospects and challenges for the implementation of AeroDrop, including a feasibility assessment of the flight-mechanics and relevant constraints at Venus, Titan, and Neptune. The study also includes an analysis of relevant past missions and a discussion of the risk reduction by using AeroDrop instead of a propulsive divert maneuver. The most promising AeroDrop configuration is shown to be passive impactor or penetrator probes delivered on a ballistic nominal trajectory as the secondary mission to a primary orbiter delivered by a lift-modulated nominal aerocapture trajectory.

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* Graduate Student, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado Center for Astrodynamics Research, 3775 Discovery Drive, 429 UCB – CCAR, Boulder, CO 80303, USA. AIAA Member.
† Professor Adjunct, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado Center for Astrodynamics Research, 3775 Discovery Drive, 429 UCB – CCAR, Boulder, CO 80303, USA. AAS Fellow, AIAA Fellow.
‡ Glenn L. Murphy Chair of Engineering, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado Center for Astrodynamics Research, 3775 Discovery Drive, 429 UCB – CCAR, Boulder, CO 80303, USA. AAS Fellow, AIAA Fellow.

**AAS 20-770**

# ENTRY VEHICLE TRAJECTORY OPTIMIZATION USING TRIGONOMETRIC-BASED REGULARIZATION

**Ehsan Taheri[*] and Kshitij Mall[†]**

A trigonometric-based regularization method is applied to the Earth entry phase, where the vehicle is subject to three state path constraints: dynamic pressure, stagnation point heat-rate, and g-load. The vehicle trajectory is controlled through modulating the angle of attack and bank angle. Presence of state and control path constraints is a challenging problem since the order and time duration of active-constraint arcs are not known a priori. The results of the proposed method are compared against a direct optimization method for a particular trajectory in which the three state path constraints and the two control input constraints become active during the maneuver.

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[*] Assistant Professor, Department of Aerospace Engineering, Auburn University, AL 36849, USA.
[†] Post-Doctoral Research Fellow, Department of Aerospace Engineering, Auburn University, AL 36849, USA.

AAS 20-771

# OPTIMAL TRAJECTORY CONTROL OF A SPACE SHUTTLE LIKE RE-ENTRY VEHICLE ENTERING TRITON

Katiyayni Balachandran* and Kamesh Subbarao†

Re-entry into the atmosphere exposes a space vehicle to several potential dangers such as combustion and mechanical failure and requires precise control of its entry trajectory. The atmospheric arc on Earth plays a pivotal role in reducing the kinetic energy by friction with the atmosphere. This paper presents the use of trajectory control methods to optimize the aerodynamic configuration of a space vehicle during atmospheric re-entry into Earth while taking into account, constraints such as thermal flux, normal acceleration, and dynamic pressure. The vehicle must be brought from an initial point (fixed longitude, and latitude) to a final manifold. Forces such as gravity and aerodynamic components like drag and lift are considered and the model is simulated to verify that the control objectives are met and the constraints satisfied. The unique dynamic history of Triton and its similarities to Earth's atmosphere made it a contender to extend the atmospheric re-entry problem to Triton. The results from this application are also presented to aid with missions to validate the thermal expansion of Triton's atmosphere.

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* Graduate Student, Department of Mechanical and Aerospace Engineering, University of Texas at Arlington, Arlington, Texas 76019, USA.

† Professor, Department of Mechanical and Aerospace Engineering, University of Texas at Arlington, Arlington, Texas 76019, USA.

# SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

# KINEMATIC AND DYNAMIC SPACECRAFT MANEUVER SIMULATORS FOR VERIFICATION AND VALIDATION OF SPACE ROBOTIC SYSTEMS

**Stephen Kwok Choon,* Markus Wilde,† Conor Safbom,‡ and Marcello Romano§**

Hardware-in-the-loop simulation and test has been an essential part in the development of spacecraft formation flight, rendezvous, capture/docking, and spacecraft robotics systems since the Gemini project. The need to recreate the kinematics and/or dynamics of spacecraft motion on the ground has led to numerous simulators and testbeds at academic institutions, government facilities, and industry laboratories. The simulation facilities range from small air-bearing tables at universities to building-sized simulators for full-scale systems tests at NASA centers. The paper presents a systematic classification of spacecraft maneuver simulators into kinematic, dynamic, hybrid, and kino-dynamic systems and provides examples for each simulator type. It then discusses two state-of-the-art simulators in detail: the Orbital Robotic Interaction, On-orbit servicing and Navigation (ORION) lab at Florida Institute of Technology, and the Proximity Operation of Spacecraft: Experimental hardware-in-the-loop Dynamic Simulator (POSEIDYN) at the Naval Postgraduate School Spacecraft Robotics Lab.

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* NRC Postdoctoral Research Associate, MAE, Naval Postgraduate School, 1 University Circle, Monterey, CA 93943, USA.
† Associate Professor, APSS, Florida Institute of Technology, 150 W University Blvd, Melbourne, FL 32901, USA.
‡ ENS, MS Student, MAE, Naval Postgraduate School, 1 University Circle, Monterey, CA 93943, USA.
§ Professor, MAE, Naval Postgraduate School 1 University Circle, Monterey, CA 93943, USA.

AAS 20-427

# ASTROBATICS: CHARACTERIZATION OF EXPERIMENTAL SELF-TOSS MANEUVERS AT THE NAVAL POSTGRADUATE SCHOOL AND NASA AMES

**Stephen Kwok Choon,* Conor Safbom,† Jonathan Chitwood,† Patrick Leary,† James Summerlin,† Daniel Watanabe,† Jonathan Barlow,‡ and Marcello Romano§**

Astrobee is a small, compact vehicle designed to operate onboard the International Space Station and perform tasks related to observation, maintenance, and hosting guest science experiments. ASTROBATICS, is an experiment led by the Spacecraft Robotics Laboratory of the Naval Postgraduate School in collaboration with NASA. ASTROBATICS is investigating self-toss hopping maneuvers to be utilized within the International Space Station in order to provide a method of locomotion. As part of the preliminary preparation, experiments were conducted at the Naval Postgraduate School and NASA Ames in order to characterize self-toss maneuvers.

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* NRC Postdoctoral Research Associate, MAE, Naval Postgraduate School, 1 University Circle, Monterey, CA 93943, USA.
† Graduate Student, MAE, Naval Postgraduate School, 1 University Circle Monterey, CA 93943, USA.
‡ Senior Aerospace Research Engineer, NASA Ames Research Center, KBR, Inc., Mail Stop 269-1 Bldg. 269 Rm. 260-25 P.O. Box 1 Moffett Field, CA 94035, USA.
§ Professor, MAE, Naval Postgraduate School, 1 University Circle Monterey, CA 93943, USA.

**AAS 20-431**

# GUIDANCE FOR AUTONOMOUS INSPECTION OF UNKNOWN UNCOOPERATIVE RESIDENT SPACE OBJECTS

**Michele Maestrini[*] and Pierluigi Di Lizia[†]**

In recent years, space debris has become an imminent and growing problem for space operations around Earth. Consequently, active debris removal and satellite servicing missions have gained increasing attention. For such scenarios, the chaser must operate autonomously in the vicinity of a non-cooperative unknown target. This paper presents a sampling-based receding-horizon motion planning algorithm that selects inspection maneuvers, while taking many complex constraints into account. The proposed guidance solution is compared with classical approaches and it is shown to take advantage of the characteristics of the natural dynamics of the relative motion to outperform them.

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[*] PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Milan via La Masa 34, 20156 (MI), Italy.
[†] Assistant Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Milan via La Masa 34, 20156 (MI), Italy.

**AAS 20-439**

# MISSION ANALYSIS OF A NEW SOLAR SAIL SATELLITE CONCEPT AT LOW EARTH ORBIT

**Halis C. Polat*, and Ozan Tekinalp†**

Exploiting the propellant free maneuver capability of solar sail satellites for high resolution Earth observation mission is addressed with an elliptical low Earth orbit. The employed orbit has a low perigee altitude for observation and a high apogee altitude for orbit maneuvers. For the purpose of mission analysis of this new concept, a reference satellite configuration is designed with an aim to determine the technological readiness level based on the characteristic acceleration. Finally, a mission orbit parameter selection algorithm for a region of interest is developed based on observation performance metrics. The new concept is shown to be successful in carrying out propellant-free Earth observation.

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* Graduate Student, Aerospace Engineering Department, Middle East Technical University, Ankara, Turkey.
† Professor, Aerospace Engineering Department, Middle East Technical University, Ankara, Turkey.

AAS 20-447

# THE EVOLUTION OF DEEP SPACE NAVIGATION: 2012-2014*

**Lincoln J. Wood†**

The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by the scientific objectives of the missions and as enabled by improvements in technology. This paper is the seventh in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from 2012 to 2014. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through 15 planetary missions.

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† Principal Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 301-121, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

**AAS 20-449**

# AUTONOMOUS ANGLES-ONLY MULTITARGET TRACKING FOR SPACECRAFT SWARMS

**Justin Kruger[*] and Simone D'Amico[†]**

This paper presents a new algorithm for autonomous multitarget tracking of resident space objects using optical angles-only measurements from a spaceborne observer. Angles-only navigation is a key enabler towards operating spacecraft swarms in deep space. However, a necessary capability, which has not yet been demonstrated, is measurement assignment for multiple target space objects in view without reliance on a-priori relative orbit knowledge. For spaceflight applications, extremely high assignment precision must be achieved using low measurement frequencies and limited computational resources. The 'Spacecraft Anglesonly MUltitarget tracking Software' (SAMUS) algorithm has been developed to meet these objectives and constraints. It enables multitarget tracking using only sequential camera images and with full autonomy by applying 1) kinematic knowledge of target behavior in the observer's reference frame, and 2) principles of multi-hypothesis tracking to treat ambiguous assignments. A measurement transform is leveraged to ensure consistent target motion and parametric curve fitting is developed for target track prediction. Kinematically-derived track gating and scoring criteria are applied to improve efficiency and performance in comparison to traditional multi-hypothesis tracking. In near-circular orbits, Monte-Carlo testing demonstrates nearly 100% assignment precision and strong recall across a range of multi-spacecraft formations, even with large data gaps and significant measurement noise. A comparison to other tracking algorithms reveals strong advantages in precision, robustness and computation time, crucial for spaceborne angles-only navigation. SAMUS will be flight tested aboard the NASA Starling1 mission in 2021.

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[*] Ph.D. Candidate, Department of Aeronautics and Astronautics, Stanford University, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, CA 94305-4035, USA.
[†] Assistant Professor, Department of Aeronautics and Astronautics, Stanford University, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, CA 94305-4035, USA.

**AAS 20-467**

# LIMB-BASED SHAPE MODELING AND LOCALIZATION FOR AUTONOMOUS NAVIGATION AROUND SMALL BODIES

**D. A. Baker[*] and J. W. McMahon[†]**

For a spacecraft on approach to a principal-axis rotating small body, limb-tracing is implemented to obtain shape observations from many different viewing angles. In this work, we show methods for building a low-resolution shape model of Itokawa based on simulated data from the Hayabusa mission, and Bennu based on simulated and real data from the OSIRIS-REx mission. We have adopted concepts from a shape from silhouette algorithm and make reasonable assumptions about lighting conditions, knowledge of body and spacecraft state, and relative orientations between the camera frame and body frame. This allows us to solve for shape, size, and range of spacecraft on approach using techniques beyond lightcurve analysis. We compare results from a SPC developed shape model to a limb-trimming model for resolving the surface from rays projected off the body edge. We also introduce a library matching algorithm for localization which is designed to be robust for irregular shapes. Both of these techniques are crucial to autonomy on approach to a small body.

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[*] Graduate Research Assistant, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, CO 80303, USA.

[†] Assistant Professor, Colorado Center for Astrodynamics Research, University of Colorado Boulder, CO 80303, USA.

# ADAPTIVE FILTER FOR OSCULATING-TO-MEAN RELATIVE ORBITAL ELEMENTS CONVERSION

**Corinne Lippe[*] and Simone D'Amico[†]**

This paper addresses the osculating-to-mean conversion of relative orbital elements (ROE) for orbits about principal axis rotators. Current approaches assume the gravity potential is dominated by $J_2$ or constrain the central body's rotation rate. To overcome limitations, an extended Kalman Filter (EKF) is presented that provides mean ROE estimates given osculating ROE measurements in quasi-stable orbits. Additionally, covariance matching is applied to tune the measurement noise and account for uncertainties in gravity. The EKF is validated using a high-fidelity orbit propagator and a Monte Carlo simulation, where accurate convergence is achieved despite the execution of maneuvers and uncertainty in gravity parameters.

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[*] PhD Candidate, Aeronautics and Astronautics, Stanford University, Durand Building 496 Lomita Mall, Stanford, CA 94305, USA.

[†] Associate Professor, Aeronautics and Astronautics, Stanford University, Durand Building 496 Lomita Mall, Stanford, CA 94305, USA.

AAS 20-508

# HIGHER ORDER STATE TRANSITION TENSORS FOR KEPLERIAN MOTION USING UNIVERSAL PARAMETERS

**Patrick Kelly,[*] Andrew J. Sinclair,[†] and Manoranjan Majji[‡]**

The inclusion of higher order state transition tensors in series approximations of nonlinear systems has proven to be useful in trajectory optimization and estimation problems. Analytical expressions for the computation of first and second order state transition tensors for Keplerian motion are derived starting from the Lagrangian coefficients expressed in terms of universal variables. These variables are applicable to any conic section. The analytical expressions derived herein are compared to numerically integrated results and validated by evaluating the known symplectic property of the state transition matrix. The application of the first and second order tensors to higher order uncertainty propagation is presented to illustrate the improvements found with the inclusion of the derived expressions.

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[*] Graduate Student Researcher, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47906, USA.

[†] Senior Aerospace Engineer, Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, NM 87117, USA.

[‡] Assistant Professor, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.

**AAS 20-514**

# AUTONOMOUS NAVIGATION AND EXPLORATION OF A SMALL NEAR-EARTH ASTEROID

**Shota Takahashi*  and Daniel J. Scheeres†**

Asteroid exploration missions must deal with large uncertainties in a target body's gravity and shape as well as ephemeris errors upon rendezvous. Navigation and guidance are typically performed as a costly ground-based operation. This paper studies the possibility of removing the ground in the process through onboard navigation with optical measurements and delta-V measurements. Several basic operations built around near-inertial hovering are considered, namely, approach from the end of an interplanetary phase, reconnaissance at various viewing geometries, close gravity estimation, and orbit insertion. Through Monte Carlo analysis, the feasibility of autonomous navigation and orbit control is evaluated.

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* Doctoral Student, Ann & H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, CO 80305-0429, USA.
† University of Colorado Distinguished Professor, Ann & H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, CO 80305-0429, USA.

AAS 20-515

# SMALL-BODY SHAPE RECOGNITION WITH CONVOLUTIONAL NEURAL NETWORK AND COMPARISON WITH EXPLICIT FEATURES BASED METHODS

**Mattia Pugliatti[*] and Francesco Topputo[†]**

Small-bodies such as asteroids and comets exhibit a wide variety of shapes and surface characteristics that are often unknown beforehand. Because of that, traditional exploration approaches do not make use of shape information on-board the spacecraft. This work would like to propose an approach based on Convolutional Neural Networks (CNN) to provide such type of information for on-board image processing and compare it with three more traditional approaches based on explicit image features such as Hu invariant moments, Fourier descriptors and polar outlines. A group of 8 different small-body shapes is chosen as archetype set and a database of images is generated to train these 4 techniques in the classification task. Their performances are then analyzed in three different scenarios. First, they are analyzed on the test set split from the database. In the second one the CNN is used to classify the shape of new objects that are not part of the archetype set. Lastly, all techniques are used under varying illumination conditions on some models from the archetype set. The CNN classifier outperforms the other methods, reaching an accuracy of 98.52 %, meaningful classification on new models and a robust behaviour under varying illumination conditions. The latter property can be used for efficient training of the CNN with a smaller database. Given the promising results, the CNN classifier is proposed for onboard implementation to provide shape information. Other important results of this work are the identification of an irregularity index for small-bodies and the definition of a shape profile as a fingerprint of the 3D object under varying perspective.

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[*] PhD Student, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156, Milan, Italy. E-mail: mattia.pugliatti@polimi.it.
[†] Associate Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156, Milan, Italy.

**AAS 20-524**

# PHYSICS-INFORMED EXTREME THEORY OF FUNCTIONAL CONNECTIONS APPLIED TO OPTIMAL ORBIT TRANSFER

**Enrico Schiassi,[*] Andrea D'Ambrosio,[†] Hunter Johnston,[‡] Mario De Florio,[§] Kristofer Drozd,[**] Roberto Furfaro,[††] Fabio Curti,[‡‡] and Daniele Mortari[§§]**

A novel and accurate physics-informed neural network method for solving differential equations, called the Extreme Theory of Functional Connections (or XTFC), is employed to solve optimal control problems. The proposed method is utilized in solving the system of differential equations resulting from the indirect method formulation of the optimal control problem, derived from the Hamiltonian function and applying the Pontryagin Maximum/Minimum Principle (PMP). The system of differential equations makes up the first order necessary conditions of the states and costates which in general produces a boundary value problem (BVPs) that is solved via X-TFC. According to the Theory of Functional Connections, the latent solutions are approximated with particular expansions, called constrained expressions. A constrained expression is a functional that both always satisfies the specified constraints and has a free-function that does not affect the specified constraints. In the X-TFC formulation, the free-function is a single-layer NN, or more precisely, an Extreme Learning Machine (ELM). Using ELMs, the unknown coefficients appear linearly and therefore, a least-square approach (for linear problems) or an iterative least-square approach (for non-linear problems) is used to compute the unknowns by minimizing the residual of the system of differential equations. In this work, the approach is validated by solving the Feldbaum problem and optimal orbit transfer problems. It is shown the major benefit of this method is the low computational time along with comparable accuracy with respect to the state of the art methods.

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[*] PhD Student, System & Industrial Engineering, University of Arizona, Tucson, AZ 85721, USA.
[†] PhD Student, School of Aerospace Engineering, Sapienza University of Rome, 00138 Rome, Italy.
[‡] PhD Student, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
[§] PhD Student, System & Industrial Engineering, University of Arizona, Tucson, AZ 85721, USA.
[**] PhD Student, System & Industrial Engineering, University of Arizona, Tucson, AZ 85721, USA.
[††] Professor, System & Industrial Engineering and Aerospace & Mechanical Engineering, University of Arizona, Tucson, AZ 85721, USA.
[‡‡] Professor, School of Aerospace Engineering, Sapienza University of Rome, 00138 Rome, Italy.
[§§] Professor, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.

AAS 20-540

# OPTIMAL INTERCEPT OF EVASIVE SPACECRAFT

**Luke Schoenwetter,* Rohan Sood,† and Brent Barbee‡**

A solution method to the orbital intercept differential game is explored. Indirect optimization techniques are combined with the dynamics of two continuous thrust spacecraft acted on by a point mass gravitational field, with these dynamics being represented by a collocation transcription. Capabilities for finding optimal solutions to the position intercept game are demonstrated, and a novel process for obtaining an initial guess is presented. The initial control histories found using this process are very similar to those of the final solution, which significantly improves convergence. The combined methods are evaluated for soundness using a simple linear environment, and then used to solve multiple orbital intercept games.

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* M.S. Student, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL 35487, USA.

† Assistant Professor, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL 35487, USA.

‡ Aerospace Engineer, Navigation and Mission Design Branch, NASA, Goddard Space Flight Center, Greenbelt, MD 20771, USA.

**AAS 20-543**

# TETHERED AEROBRAKING DESIGN FOR REPEATABLE MANEUVERS

**Lluís Umbert i Amat[*] and Steven Tragesser[†]**

An aerobraking maneuver performed with a tethered system has the benefit of allowing for an increase in the drag for a given center of mass orbit by dropping the lower subsatellite into the denser atmosphere. One challenge of this system is that the aerodynamic drag imparts an angular impulse on the system that is always in the direction of the orbital angular momentum. If successive aerobraking passes for sustained operations are desired, e.g. in a debris elimination satellite, then this buildup of angular momentum must be counteracted. This work develops a tether length control law during the exoatmospheric flight that counteracts the drag angular impulse. The design of the control law requires numerical solution of nonlinear equations, but newly developed analytics provide an estimate that reduces computational time and increases the robustness of the algorithm. The results show that the nearly periodic state that is required for successive passes can be achieved for practical tether lengths and power requirements.

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[*] Graduate Student of Mechanical and Aerospace Engineering, University of Colorado, Colorado Springs, Colorado Springs, CO 80918, USA.

[†] Associate Professor of Mechanical and Aerospace Engineering, University of Colorado, Colorado Springs, Colorado Springs, CO 80918, USA.

AAS 20-557

# COMPLETE ENERGY OPTIMAL LANDING ON SMALL AND LARGE PLANETARY BODIES VIA THEORY OF FUNCTIONAL CONNECTIONS

**Enrico Schiassi,*  Andrea D'Ambrosio,† Hunter Johnston,‡ Roberto Furfaro,§ Fabio Curti,** and Daniele Mortari††**

In this paper, we propose a unified approach to solve the energy optimal landing on a planetary body (e.g., planet, asteroid, comet, etc.). The proposed method accurately computes the energy optimal landing trajectories, including the optimal time of flight, with a computation time on the order of 10-100 milliseconds, using MATLAB. The speed and accuracy of this techniques validate it as a suitable approach for real-time applications. The algorithms developed from this theory are validate for the landing final descent phase in Gaspra and Bennu asteroids and planet Mars.

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* PhD Student, System & Industrial Engineering, University of Arizona, Tucson, AZ 85721, USA.
† PhD Student, School of Aerospace Engineering, Sapienza University of Rome, 00138 Rome, Italy.
‡ PhD Student, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
§ Professor, System & Industrial Engineering and Aerospace & Mechanical Engineering, University of Arizona, Tucson, AZ 85721, USA.
** Professor, School of Aerospace Engineering, Sapienza University of Rome, 00138 Rome, Italy.
†† Professor, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.

**AAS 20-569**

# A PARTICLE FILTERING APPROACH TO SPACE-BASED, MANEUVERING SATELLITE LOCATION AND ESTIMATION

**Zach Hall,[*] Kirk Johnson,[†] and Puneet Singla[‡]**

In the highly cluttered environment of frequently used Low Earth Orbit (LEO) and Geosynchronous Equatorial Orbit (GEO), the need for heightened space-based Space Situational Awareness (SSA) capabilities is an increasingly important aspect of maintaining superiority in the space domain. This paper lays out the mathematical framework for a probability-based automated search and estimation algorithm in the case of an actively maneuvering target satellite. Specifically, the case of a space-based observer in a relative reference frame is considered. A particle filter (PF) is used to estimate and update an approximation of the target satellite probability density function (pdf) in the presence of highly nonlinear observation and dynamic models. Reachability set theory for impulsive maneuvers is applied in conjunction with the PF algorithm to alleviate some of the computational burden associated with classical PF's providing a feasible and accurate option for nonlinear scenarios. Attitude control of the observer spacecraft is formulated as a greedy maximum likelihood optimization problem for computational feasibility. Simulations for both LEO and the GEO cases are presented and discussed in detail.

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[*] Graduate Student in Penn State University's Department of Aerospace Engineering and Visiting Researcher at the Air Force Institute of Technology (AFIT), State College PA 16802, USA. E-mail: zyh5059@psu.edu.
[†] Assistant Professor of Aerospace Engineering, Department of Aeronautics and Astronautics, AFIT, Wright-Patterson AFB, OH 45433, USA.
[‡] Associate Professor, AIAA Associate Fellow, AAS Fellow, Department of Aerospace Engineering, Pennsylvania State University, State College, PA 16802, USA. E-mail: psingla@psu.edu.

AAS 20-572

# CHARACTERIZATION AND OPTIMIZATION OF EFFICIENT CHANCE-CONSTRAINED NAVIGATION STRATEGIES FOR LOW-ENERGY TRANSFERS

**Riley M. Fitzgerald,[*] Philip D. Hattis,[†] Kerri L. Cahoy,[‡] and Richard Linares[§]**

Low-energy transfers expose a spacecraft to long periods of unstable dynamics, and navigation along them currently relies on frequent tracking by expensive ground infrastructure. This paper characterizes minimum-cost navigation strategies for these trajectories, subject to constraints on the probability of transfer success. First, stochastic augmented state dynamics are developed to model the behavior of a spacecraft with a given measurement and correction strategy. Secondly, Monte-Carlo simulations of a sample correction schedule over an example transfer are presented, demonstrating the characteristic $\Delta v$ and estimator error profiles. Finally, a method for chance-constrained optimization is presented, resulting in the minimum-cost tracking windows and correction times guaranteeing a specified probability of success.

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[*] Doctoral Candidate, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, and Draper Fellow, The Charles Stark Draper Laboratory, Inc. Cambridge, MA 02139, USA.
[†] Laboratory Technical Staff, Space and Mission Critical Systems, The Charles Stark Draper Laboratory, Inc. Cambridge, MA 02139, USA.
[‡] Associate Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
[§] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

**AAS 20-580**

# USING THE GMAT APPLICATION PROGRAMMER'S INTERFACE

**Darrel J. Conway* and John McGreevy†**

The General Mission Analysis Tool (GMAT) is an open-source astrodynamics tool, developed in partnership between NASA's Goddard Space Flight Center (GSFC), industry partners, and academic institutions.1 GMAT is in operational use in the GSFC Flight Dynamics Facility, providing guidance and navigation support for active missions, and as a mission design tool at NASA and industrial organizations.

The GMAT R2020a release includes a new GMAT Application Programming Interface (API) that provides access to core GMAT capabilities from Python and Java, and, through the Java interface, from MATLAB. GMAT's API is a tested and documented beta-quality feature of the 2020 release. It includes sample scripts that can be executed in Python or MATLAB, tutorial walk-throughs presented as interactive notebooks, and more than 70 pages of user documentation. The GMAT API can also be run interactively. When working with the tool in this mode, users have access to a live help system that presents available options to the user to simplify use of the system. Configuration for the GMAT API is straightforward on Linux, Windows, and Mac workstations. This paper presents these features and several use cases for the GMAT API.

One core feature of the GMAT API is the access to GMAT's core components for direct manipulation and use. Access to GMAT's components enables the development of tutorial materials, presented as Jupyter notebooks, that introduce users to GMAT's components and walk users through interactive use of these components using the native user interface elements of Python or MATLAB. The GMAT API provides a toolkit to build graphical tools hosted in language native environments. Access to GMAT's computational models for propagation and navigation models enable use of those features for analysis of a user's data, including live streaming of measurements into custom tools to validate those data streams in real time. This API provides users with easy access to a library of astrodynamics utilities that are rigorously tested and trusted operationally by a wide range of NASA and private missions, reducing the need for individual users to implement and test their own utilities. These utilities range from time system conversions, to coordinate system conversions, all the way to simulating measurements including corrections such as light-time delays and relativistic corrections.

All of the GMAT scripting capabilities are accessible using the GMAT API. The script interfaces enable simple configuration of large scale analysis problems, ranging from scans of parameters to explore a solution space to more complex problems like Monte-Carlo analyses. These capabilities are presented with sample problems designed to illustrate their use.

Current work on the GMAT API includes integration of GMAT and Monte into a unified environment, driven from Monte's Python based tool set. The status of this work is also described in this paper.

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* Senior Scientist and CEO, Thinking Systems, Inc., 437 W Thurber Rd., Suite 6, Tucson, AZ 85705, USA.
† Aerospace Engineer, Emergent Space Technologies, Inc., 7901 Sandy Spring Road, Suite 511, Laurel, MD 20707, USA.

# IMAGE-BASED OPTIMAL POWERED DESCENT GUIDANCE VIA DEEP RECURRENT IMITATION LEARNING

**Luca Ghilardi,[*] Andrea D'Ambrosio,[†] Andrea Scorsoglio,[‡] Roberto Furfaro,[§] Richard Linares,[**] and Fabio Curti[††]**

Future missions to the Moon and Mars will require autonomous landers/rovers to perform successful landing manoeuvres. In order to accomplish this task, reliable, fast and autonomous Guidance, Navigation, and Control (GNC) algorithms are necessary. In recent years, the strong capabilities of modern hardware have allowed employing deep learning models for space applications. In this paper, we present an image-based powered descent guidance via deep learning to control the command acceleration along the three axes. In particular, a hybrid architecture, composed of a Convolutional Neural Network and a Long Short Term Memory (CNN-LSTM), is trained using, as inputs, sequences of images taken during the descent. Hence, the neural network maps the sequences of images into the values of the command acceleration. The images are generated within a simulated environment with physically based ray-tracing capabilities.

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[*] PhD Student, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, AZ 85721, USA.
[†] PhD Candidate, School of Aerospace Engineering, Sapienza University of Rome, Via Salaria 851, 00138 Rome, Italy.
[‡] PhD Student, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, AZ 85721, USA.
[§] Professor, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, AZ 85721, USA.
[**] Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA.
[††] Professor, School of Aerospace Engineering, Sapienza University of Rome, Via Salaria 851, 00138 Rome, Italy.

AAS 20-619

# ADAPTIVE ATTITUDE CONTROL OF LAUNCH VEHICLES IN ATMOSPHERIC FLIGHT

Domenico Trotta,* Alessandro Zavoli,† Guido De Matteis,‡
and Agostino Neri§

The inclusion of an adaptive augmenting control (AAC) component in the flight control system (FCS) of launch vehicles can be highly effective for enhancing control stability and robustness with respect to parametric uncertainties and dealing with off-nominal conditions, so as to extend the envelope of failures and flight anomalies that can be managed by the vehicle control system. In this paper the adoption of an adaptive notch filter in a control architecture consisting of proportional-derivative (PD) elements, bending filters and AAC is proposed and discussed. The main goal of the study is to investigate the feasibility of implementation and the possible benefits of filter adaptation, such as overcoming critical limitations that degrades the AAC effectiveness for large uncertainties on elastic mode characteristics. To this end, the frequency of first bending mode is estimated during the flight in order to adapt the design parameters of the notch filter. Adaptive control performance is evaluated by simulation of vehicle motion in the atmospheric flight phase in selected stressing cases. Results of Monte Carlo simulations are also discussed for a broader assessment of the effects of adaptive filter on the robustness of integrated FCS.

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* Ph.D. Student, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana 18 - 00184, Rome, Italy. E-mail: domenico.trotta@uniroma1.it.
† Research Fellow, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana 18 - 00184, Rome, Italy. E-mail: alessandro.zavoli@uniroma1.it.
‡ Professor, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana 18 - 00184, Rome, Italy. E-mail: guido.dematteis@uniroma1.it.
§ Head of VEGA-C Launcher System Integration and Launch System Synthesis Office, VEGA Integrated Project Team, ESRIN Largo Galileo Galilei, 1 - I-00044, Frascati (Rome), Italy. E-mail: agostino.neri@esa.int.

**AAS 20-633**

# A SQUARE-ROOT FACTORIZED MULTIPLICATIVE EXTENSION TO THE PARTICLE FLOW FILTER

**Kari C. Ward[*] and Kyle J. DeMars[†]**

Particle-based methods for recursive Bayesian estimation provide a means to obtain precise solutions in challenging problems. The subset of particle flow filters compute the Bayesian update by modeling the motion of the samples from their *a priori* locations through the state space to represent the *a posteriori* beliefs. This work expands the filtering capabilities of the particle flow estimation framework, specifically in the context of the recently developed information flow variant. A means of incorporating attitude estimation mathematically consistent with the underlying parameterization is developed in addition to a square-root factorized flow model to promote numerically stable uncertainty representation. An entropy-based convergence control for the flow is also presented that circumvents the need for ad hoc selection of an underweighting-like parameter. The resulting square-root factorized, multiplicative information flow filter with convergence control is applied to a lunar descent-to-landing navigation simulation to demonstrate the new capabilities and resulting performance.

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[*] Graduate Student, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA.
[†] Associate Professor, Department of Aerospace Engineering, Texas A&M University, College Station, TX, 77843, USA.

**AAS 20-642**

# STATIONKEEPING IN EARTH-MOON NEAR RECTILINEAR HALO ORBITS

**Vivek Muralidharan[*] and Kathleen C. Howell[†]**

Near Rectilinear Halo Orbits (NRHOs) are stable or nearly stable orbits that are defined as part of the L1 and L2 halo orbit families in the circular restricted three-body problem. Within the Earth-Moon regime, the L2 NRHOs offer candidate trajectories for the upcoming Gateway mission. The spacecraft, however, incurs continuous deviations due to unmodeled forces and orbit determination errors in this dynamically sensitive region. The current investigation focuses on a technique to maintain the spacecraft near a virtual reference orbit despite these uncertainties. For the stationkeeping scheme, flow dynamics in the region are utilized to categorically identify appropriate maneuver and target locations. The investigation reflects the impact of various factors on maneuver cost and efficacy. Additional feedback control is applied for phasing constraints.

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[*] Ph.D. Candidate, School of Aeronautics and Astronautics, Purdue University, Neil Armstrong Hall of Engineering, 701 W. Stadium Ave., West Lafayette, IN 47907, USA. E-mail: muralidv@purdue.edu.

[†] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, Neil Armstrong Hall of Engineering, 701 W. Stadium Ave., West Lafayette, IN 47907, USA. E-mail: howell@purdue.edu.

**AAS 20-646**

# NASA'S SPACE LAUNCH SYSTEM OPENS NEW FRONTIERS FOR HIGH C3 SCIENCE MISSIONS TO DEEP SPACE

**Kimberly Robinson* and Robert W. Stough†**

NASA's Space Launch System (SLS), an evolvable super heavy-lift vehicle that will be available with an 8.4 m diameter payload fairing, can achieve high C3 launches to provide the science community with new capabilities for sending probes to the outer solar system – or even interstellar space. Initially, the SLS Block 1 vehicle will launch at least 27 metric tons (t) to trans-lunar injection (TLI) using a propulsion system of two solid rocket boosters, four liquid hydrogen (LH2)/liquid oxygen (LOX) RS-25 engines and a single-engine LH2/LOX upper stage. A more powerful four-engine LH2/LOX upper stage, and other upgrades, on the evolved Block 1B vehicle will increase mass to TLI capability to at least 42 t. The Block 2 vehicle will incorporate evolved solid rocket boosters to increase mass to TLI to 46 t. The Block 1B/Block 2 vehicles will provide unprecedented volume for payloads, and additional upper stages, in 8.4 m diameter payload fairings in 19.1 m and 27.4 m lengths. Recent studies performed by the Advanced Concepts Office (ACO) and the Spacecraft/Payload Integration & Evolution (SPIE) office at NASA's Marshall Space Flight Center (MSFC), have shown that packaging an additional LH2/LOX upper stage and a solid-motor kick stage with a science probe can enable a mission to reach C3 performance as high as 300 km2/sec2 – nearly double the C3 of the New Horizons probe to Pluto and the Kuiper Belt. This new level of performance opens trade space for a new generation of previously impossible missions, allowing mission planners the flexibility to trade mass, volume and transit time as well as take advantage of greater availability of launch windows.

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* Dr., Manager, Payload Integration, NASA's Space Launch System, XP50, Marshall Space Flight Center, AL 35802, USA.

† Manager, SLS Utilization, NASA's Space Launch System, XP50, Marshall Space Flight Center, AL 35802, USA.

**AAS 20-647**

# CONVEX OPTIMIZATION OF LAUNCH VEHICLE ASCENT TRAJECTORY WITH HEAT-FLUX AND SPLASH-DOWN CONSTRAINTS

**Boris Benedikter,[*] Alessandro Zavoli,[†] Guido Colasurdo,[‡] Simone Pizzurro,[§] and Enrico Cavallini[**]**

This paper presents a convex programming approach to the optimization of a multistage launch vehicle ascent trajectory, from the liftoff to the payload injection into the target orbit, taking into account multiple nonconvex constraints, such as the maximum heat flux after fairing jettisoning and the splash-down of the burned-out stages. Lossless and successive convexification are employed to convert the problem into a sequence of convex subproblems. Virtual controls and buffer zones are included to ensure the recursive feasibility of the process and a state-of-the-art method for updating the reference solution is implemented to filter out undesired phenomena that may hinder convergence. A *hp* pseudospectral discretization scheme is used to accurately capture the complex ascent and return dynamics with a limited computational effort. The convergence properties, computational efficiency, and robustness of the algorithm are discussed on the basis of numerical results. The ascent of the VEGA launch vehicle toward a polar orbit is used as case study to discuss the interaction between the heat flux and splash-down constraints. Finally, a sensitivity analysis of the launch vehicle carrying capacity to different splash-down locations is presented.

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[*] PhD Student, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana 18, Rome, 00184, Italy. E-mail: boris.benedikter@uniroma1.it.

[†] Research Assistant, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana 18, Rome, 00184, Italy. E-mail: alessandro.zavoli@uniroma1.it.

[‡] Full Professor, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana 18, Rome, 00184, Italy. E-mail: guido.colasurdo@uniroma1.it.

[§] Research Fellow, Launchers and Space Transportation Department, Italian Space Agency, Via del Politecnico snc, Rome, 00133, Italy. E-mail: simone.pizzurro@est.asi.it.

[**] Head of Scientific Research Department, Italian Space Agency, Via del Politecnico snc, Rome, 00133, Italy. E-mail: enrico.cavallini@asi.it.

# ICE GIANT EXPLORATION VIA AUTONOMOUS OPTICAL NAVIGATION*

Daniel P. Lubey,† Shyam Bhaskaran,† Nicholas Bradley,† and Zubin Olikara‡

Long communication delays and the expense of supporting large-scale, human-managed spacecraft operations are significant impediments to deep-space exploration; however, implementing autonomy on-board the spacecraft can help overcome these hurdles. In this study, we investigate the feasibility of using on-board autonomous optical navigation techniques during approach to and proximity operations around the ice giants (i.e., Uranus and Neptune) while using the planets' satellites as optical beacons. Using beacon visibility and navigation uncertainties as metrics, we show what requirements (e.g., camera properties and beacon uncertainties) are needed to make these autonomously navigated missions feasible.

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† Outer Planet Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

‡ Inner Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

AAS 20-675

# DEEP CONVOLUTIONAL TEMPLATE MATCHING UNDER CHALLENGING LIGHTING CONDITIONS

Jonathan Manni,* Jay McMahon,† Nisar Ahmed,‡
Rebecca Russell,§ and Courtney Mario**

Limitations exist in using conventional template matching methods like normalized cross correlation (NCC) to identify the location of pre-defined image templates in camera images during flight, particularly in cases where lighting conditions between the template and camera image differ largely. This work investigates using a convolutional neural network to address the problem of identifying templates in camera images under these challenging lighting conditions. A network architecture is implemented and trained toward this end and its accuracy in identifying templates under challenging lighting conditions is shown to improve upon that of NCC. A simulation is developed for validating the performance of using our method for terrain relative navigation around the Moon.

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* Graduate Research Assistant, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Drive, AERO 442, Boulder, CO 80309, USA.
† Assistant Professor, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Drive, AERO 461, Boulder, CO 80309, USA.
‡ Assistant Professor, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Drive, AERO 265, Boulder, CO 80309, USA.
§ Senior Member of the Technical Staff, Draper, 555 Technology Square, Cambridge, MA 02139, USA.
** Principal Member of the Technical Staff, Draper, 555 Technology Square, Cambridge, MA 02139, USA.

AAS 20-750

# EXPERIMENTAL CONFIRMATION OF A NOVEL TRANSCENDING PARTICLE SWARM OPTIMIZATION (TPSO) ALGORITHM FOR EXTRATERRESTRIAL SURFACE SEARCH AND EXPLORATION

**Gregory Hatfield,* Kyle Sanders,† and May-Win L. Thein‡**

Particle Swarm Optimization (PSO) is a heuristic optimization algorithm originally created to mimic the swarm behavior of natural phenomena, such as flocks of birds and schools of fish. In previous works at the University of New Hampshire, the use of PSO as an extraterrestrial resource prospecting methodology was explored and experimentally confirmed using a fleet of high fidelity land rovers. For any extraterrestrial application, power and time efficiency are vital considerations due to limited power generation and inflexible mission windows. In this paper, the authors propose a novel adaptation of the PSO algorithm using combinatorial optimization to significantly improve energy efficiency and reduce time to convergence in experimental application. Experimental field test results show that the TPSO results in marked improvement in both energy and time efficiency over that of the previously experimentally confirmed PSO algorithm.

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* Graduate Student of Mechanical Engineering, University of New Hampshire, Durham, NH 03824, USA. AIAA Student Member.
† Graduate Student of Mechanical Engineering, University of New Hampshire, Durham, NH 03824, USA. AIAA Student Member.
‡ Associate Professor of Mechanical Engineering, University of New Hampshire, Durham, NH 03824, USA. AIAA Senior Member.

**AAS 20-754**

# CUBESAT EXPLORATION MISSIONS TO BINARY ASTEROIDS: ON BOARD AUTONOMY AND INTELLIGENT IMAGING TOWARDS SCIENCE RETURN ENHANCEMENT

**Margherita Piccinin,[*] Giovanni Zanotti,[†] Stefano Silvestrini,[‡] Andrea Capannolo,[§] Andrea Pasquale,[**] and Michèle Lavagna[††]**

CubeSats exploitation for small bodies exploration may contribute to gather high value scientific data, but entails significant challenges for the GNC system, due to uncertain environment and currently limited technology capabilities of such small platforms. This paper proposes an autonomous navigation and pointing control for a CubeSat operating in close proximity of a binary system. An AI-based policy is included in the GNC system, to maximize the mission scientific return with autonomous decision making of the next best image acquisition time. The proposed approach considers typical CubeSat hardware capabilities and relies on light and robust algorithms.

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[*] PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Italy.
E-mail: margherita.piccinin@polimi.it.
[†] PhD Candidate, Department of Aerospace Science and Technology, giovanni.zanotti@polimi.it.
[‡] PhD Candidate, Department of Aerospace Science and Technology, stefano.silvestrini@polimi.it.
[§] PhD Candidate, Department of Aerospace Science and Technology, andrea.capannolo@polimi.it.
[**] PhD Candidate, Department of Aerospace Science and Technology, andrea.pasquale@polimi.it.
[††] Full Professor, Department of Aerospace Science and Technology, michelle.lavagna@polimi.it.

AAS 20-772

# REMARKS ON THE FEASIBILITY OF OBTAINING STARNAV MEASUREMENTS WITHIN THE SOLAR SYSTEM

**Hoang Nguyen,[*] Michael W. Kudenov,[†] and John A. Christian[‡]**

The StarNAV concept provides a means for estimating the velocity of a spacecraft anywhere in the Solar System (or beyond) by the relativistic perturbation of starlight. While different system configurations exist, the most robust known approach considers only the apparent change in the angle between stars due to stellar aberration. The small change in inter-star angle used for StarNAV is measurable with modern scientific instruments, but it remains to be seen if this is attainable with a navigation sensor. This work provides an end-to-end error budget for a simple StarNAV sensor system and identifies area where future development is required.

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[*] Graduate Research Assistant, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27606, USA.
[†] Associate Professor, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27606, USA.
[‡] Associate Professor, Department of Mechanical, Aerospace, Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA.

AAS 20-775

# DESIGN OF ON-BOARD OXIDIZER-FUEL MASS ESTIMATION ALGORITHM FOR A LUNAR LANDING MISSION

**Deepana Gandhi,[*] Yogeshwaran J,[†] Vishesh Vatsal,[‡] and Natarajan P[§]**

TeamIndus (TI)'s Lunar Logistics program envisions multiple lunar missions over the coming years to meet commercial and scientific requirements. The mission profile for the first lunar mission can be split into the orbital phase, which brings the spacecraft to the desired entry conditions of lunar descent, and the autonomous powered descent phase which delivers the lander safely to the desired landing site. The descent phase is split into multiple sub-phases among which the approach phase is critical. During this phase, the vehicle uses a closed loop guidance scheme to remove inherited dispersions and bring it to a targeted position and velocity. The realization of the acceleration demand from the guidance logic into commands for the Reaction Control Thrusters (RCTs) requires an estimate of the spacecraft mass. Tight constraints on mass, cost and schedule require this problem to be addressed through on-board estimation. This paper discusses two methods for real time online vehicle mass estimation. Both the methods have a predictor-corrector structure, wherein the standard mass flow rate equations are used to propagate the mass estimate, with the correction to the estimated mass being computed from measurements provided by an Inertial Measurement Unit (IMU). The first method - Mass Estimation by Direct Update applies the relationship to directly compute the correction, while the second method - Mass Estimation via Bounds Propagation provides an estimate of the vehicle mass by applying the relationship to progressively reduce the uncertainty bounds of mass and delivered impulse. Additionally, this method enables simultaneous reduction in the uncertainties of estimated thrust of the Main Engine. The performance of the both the algorithms is examined through high fidelity simulations of the lunar descent maneuver containing various sensor errors (noise, bias, and misalignment), actuator errors (thrust magnitude deviation and roughness) and information latency in the system. A comparative analysis is done to conclude on the best algorithm suitable for the mission.

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[*] Guidance, Navigation and Controls Engineer, Axiom Research Labs Pvt Ltd, Bangalore, India.
[†] Guidance, navigation and Controls Engineer, Axiom Research Labs Pvt Ltd, Bangalore, India.
[‡] Guidance, navigation and Controls Engineer, Axiom Research Labs Pvt Ltd, Bangalore, India.
[§] Head, Guidance, Navigation and Controls Engineer, Axiom Research Labs Pvt Ltd, Bangalore, India.

AAS 20-776

# OPTIMAL CONTROL OF REPEAT GROUND-TRACK ORBIT IN HIGH-FIDELITY DYNAMICAL MODEL VIA SECOND-ORDER CONE PROGRAMMING

**Roberto Armellin,* Yanchao He,† and Ming Xu‡**

A method for the design and control for Repeat Ground-Track (RGT) orbits in high-fidelity dynamics is presented. The method is based on the use of the high-order expansion of Poincaré maps to propagate regions of the phase space forward in time for one, or more, repeating cycles. This allows us to identify initial conditions than ensure the repetition of ground-tracks with high accuracy. These conditions are targeted by the spacecraft with a multiple-impulse control strategy that is optimized via Second-Order Cone Programming (SOCP). The resulting approach is suitable for both high- and low-thrust propulsion systems and can be implemented onboard thanks to the convex formulation of the problem.

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* Professor, ISAE-SUPAERO, 10 Avenue Édouard-Belin, 54032 - 31055, Toulouse, France.
† Engineer, Orbit Design Group, DFH Satellite Co., Ltd., 100094 Beijing, People's Republic of China.
‡ Associate Professor, School of Astronautics, Beihang University, 100191 Beijing, People's Republic of China.

**AAS 20-778**

# OPTIMUM ENGINE CONFIGURATION FOR SCIENTIFIC PAYLOAD DELIVERY LUNAR LANDERS

**Barath Charles,[*] Vishesh Vatsal,[†] Kiran S Pazhayattinkal,[‡] Alnawazkhan A,[§] Rakeshh Mohanarangan,[**] P. Natarajan,[††] and M. Jayaraman[‡‡]**

There is a renewed interest from private and government agencies across the globe to send large robotic missions to the Moon with goals of exploration, in-situ resource utilization (ISRU) and lunar science. This paper attempts to be a guideline for propulsion configuration design to ensure reliable, repeatable and safe payload delivery in the range of 50 – 1000kg to the lunar surface. An optimal engine configuration would arise from a trade-off between performance, availability, readiness of vendors, cost-effectiveness, component realization lead-time, system AIT (Assembly, Integration and Testing), operational complexity, system reliability and payload capacity. This paper considers various propellant combinations and system operational modes like unified, dual mode and hybrid, along with other system parameters to calculate a performance metric. Minimum launch mass required for an effective system thrust and specific impulse combination to deliver a given payload mass is derived. Performance metrics are generated for a range of configurations for the same payload requirement to contrast various designs, it is found that the optimum engine configuration should have an overall performance metric $P \geq 0.8$.

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[*] Engineer, Guidance, Navigation and Control, Axiom Research Labs, Bangalore, India.
E-mail: barath.c@teamindus.in.
[†] Engineer, Guidance, Navigation and Control, Axiom Research Labs, Bangalore, India.
E-mail: vishesh.vatsal@teamindus.in.
[‡] Engineer, Propulsion, Axiom Research Labs, Bangalore, India. E-mail: kiran.pazhayattinkal@teamindus.in.
[§] Engineer, Propulsion, Axiom Research Labs, Bangalore, India: E-mail: alnawaz.khan@teamindus.in.
[**] Engineer, Propulsion, Axiom Research Labs, Bangalore, India. E-mail: rakeshh.mohanarangan@teamindus.in.
[††] Expert, Guidance, Navigation and Control, Axiom Research Labs, Bangalore, India. E-mail: pn@teamindus.in.
[‡‡] Expert, Propulsion, Axiom Research Labs, Bangalore, India. E-mail: mj@teamindus.in.

# ORBIT DETERMINATION AND SPACE SURVEILLANCE

**AAS 20-406**

# NONLINEAR FILTERING OF LIGHT-CURVE DATA

**Sehyun Yun*** **and Renato Zanetti†**

A particle filter with an expectation-maximization (EM) clustering algorithm for Gaussian mixture models (GMMs) is proposed to simultaneously estimate the position, velocity, attitude, angular rates, and surface parameters of a space object (SO) in the near-Geostationary Earth Orbit (GEO). Recent work shows that the unscented Kalman filter applied to this problem diverges due to information dilution in the presence of many uncertain states to be estimated at once. The underlying reasons of the filter divergence have not yet been completely revealed. Under the scenario considered in this paper, it is demonstrated through numerical simulation that the underlying reason for the filter divergence in SO tracking is due to the severe nonlinearities of light-curve measurement data coupled with weak observability; rather than information dilution. In addition, two alternative estimation techniques based on modifications of the extended Kalman filter (EKF) and unscented Kalman filter (UKF) are introduced to reduce the computational burden while still mitigating filter divergence.

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* Ph.D. Candidate, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA.

† Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA.

**AAS 20-417**

# DA-BASED MULTIPLE GAUSSIANS PARTICLE FILTER FOR ORBIT DETERMINATION

**Simone Servadio[*] and Renato Zanetti[†]**

The nonlinear filtering problem plays a fundamental role in multiple space related applications. This paper offers a new filtering technique that combines the classical ensemble Kalman filter with a Gaussian mixture model. Differential Algebra (DA) techniques are used as a tool to reduce the computational effort required by particle filters. Moreover, the use of Expectation Maximization (EM), as a clustering algorithm, leads to a better approximation of the propagated probability density function and to a multiple weighted measurement update. The performances of the new method are assessed in the nonlinear Orbit Determination problem, for the challenging case of low observations frequency.

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[*] Ph.D. Candidate, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA.
[†] Assistant Professor, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, USA.

**AAS 20-440**

# RESULTS OF THE DEEP SPACE ATOMIC CLOCK DEEP SPACE NAVIGATION ANALOG EXPERIMENT

**Jill Seubert,[*] Todd Ely[†] and Jeffrey Stuart[‡]**

The timing and frequency stability provided by the Deep Space Atomic Clock (DSAC) is almost comparable with the Deep Space Network's ground clocks, and will enable one-way radiometric measurements with accuracy equivalent to current two-way tracking data. A demonstration unit of the clock was launched into low Earth orbit on June 25, 2019, for the purpose of validating DSAC's performance in the space environment. GPS data collected throughout the mission was utilized not only for precise clock estimation, but also as a proxy for deep space tracking data to conduct the Deep Space Navigation Analog Experiment. Through careful processing of GPS Doppler data and limited modeling fidelity representative of deep space navigation capabilities, the analog orbit solutions are compared to higher-fidelity solutions, demonstrating DSAC's viability as a navigation instrument in conditions typical for a low altitude Mars orbiter.

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[*] Deputy Principal Investigator, Deep Space Atomic Clock Technology Demonstration Mission, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.
[†] Principal Investigator, Deep Space Atomic Clock Technology Demonstration Mission, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.
[‡] Investigation System Engineer, Deep Space Atomic Clock Technology Demonstration Mission, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

AAS 20-458

# COMPARISON OF GAUSSIAN SUM FILTER AND THE METHOD OF CHARACTERISTICS FILTER FOR SPACE OBJECT UNCERTAINTY PROPAGATION

Nagavenkat Adurthi*

In this paper, the recently developed Method of Characteristics Filter (MOCF) is compared with Gaussian Sum Filter (GSF) to propagate uncertainty for Resident Space Objects (RSOs). The dynamical motion of an RSO, ideally governed by the two body equation, is nonlinear and results in significant non-Gaussian shaped probability density function (PDF) for the state uncertainty. Conventional filtering algorithms often approximate the state PDF as Gaussian for ease of computation while forgoing accuracy and information in higher order moments of the underlying state uncertainty. For high performance and precision applications, such as conjunction probability assessment, it is often required to compute this non-Gaussian state PDF. To this end, we compare the efficacy of the conventional GSF with our recently developed MOCF to propagate the non-Gaussian uncertainty for the two body problem. The MOCF is based on the method of characteristics to efficiently solve the corresponding Liouville Equation (LE) of the two body problem by only propagating the state PDF value for few characteristic curves. Further, the MOCF uses fast regression methods to estimate the full state PDF surface from these characteristic solutions. The primary comparison metric is the ability to accurately propagate the PDF value and not just the contours of the state PDF. Numerical simulations that compare computational cost with accuracy are used to illustrate both the approaches.

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* Assistant Professor, Mechanical and Aerospace Engineering, University of Alabama in Huntsville, Huntsville, AL 35899, USA. E-mail: na0043@uah.edu.

**AAS 20-487**

# CISLUNAR PERIODIC ORBIT ANALYSIS FOR PERSISTENT SPACE OBJECT DETECTION CAPABILITY

**Jacob K. Vendl[*] and Marcus J. Holzinger[†]**

This work studies the performance of periodic orbits to conduct Space Traffic Management in cislunar space, with the aim of finding a preferable trajectory for detection, tracking, initial orbit estimate formation, and orbit estimate maintenance. A mathematical measure is developed to quantitatively evaluate a given trajectory's capability to observe cislunar space and used to study multiple families of periodic orbits. A key finding is that retrograde periodic orbits possessing m:n resonance with the Moon's synodic period possess excellent characteristics for cislunar observation. Certain L1 and L2 Lyapunov trajectories are near-optimal when evaluated for observational capability and stability.

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[*] Graduate Student, Ann & H.J. Smead Aerospace Engineering Sciences Department, 3775 Discovery Drive, Boulder, CO, 80309, USA. AIAA Student Member.
[†] Associate Professor, H. Joseph Smead Faculty Fellow, Ann & H.J. Smead Aerospace Engineering Sciences Department, 3775 Discovery Drive, Boulder, CO, 80309, USA. AIAA Associate Fellow.

**AAS 20-500**

# DATA ASSOCIATION EXPERIMENTS USING REAL RADAR DATA

**Benedikt Reihs,[*] Alessandro Vananti,[†] Thomas Schildknecht,[‡]
Jan A. Siminski,[§] and Tim Flohrer[**]**

The monitoring of the space object population, especially the space debris population, is an important aspect of space safety to enable the safe operation of near-Earth space missions. One of the main components of such a space surveillance system is the maintenance of a space object database, commonly called catalogue, which can be used for e.g. conjunction assessment and re-entry casualty risk estimation. The build-up and maintenance of such a database requires the continuous, automated processing of observations to create new database entries and maintain the accuracy of existing ones.

To support the initialisation of new objects into the database, it is advantageous to use multiple passes of an object to have a more reliable orbit compared to that from a single pass. To identify such associated passes, previous work by the authors include the development of a method to test whether two measured passes, called tracklets, originate from the same object in which case they are called to be correlated. This method was tested on simulated measurement data and showed promising results. The present paper uses real radar measurements from two LeoLabs radars in the United States to further validate and characterise the method, mainly for objects in low earth orbit. The first tests confirm that the method's initial orbit determination which includes the secular J2-perturbation works for the maximum time span of circa 24 days between two tracklets. The correlation which also requires the selection of the correct number of revolutions between the two tracklets works reliably for 1-2 days before the selection of a wrong number of revolutions increases, which is also dependent on the geometry of the two passes. Further experiments test the sensitivity of the method to e.g. distributed stations, atmospheric drag and manoeuvres. Finally, different approaches to a cold-start of a database are tested using either least squares orbit determination or a graph network for object confirmation. Overall results show that the developed methods works well with real radar data and can contribute to the build-up of a space object database.

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[*] PhD Student, Astronomical Institute University of Bern (AIUB), Sidlerstrasse 5, 3012 Bern, Switzerland.
[†] Research Associate, Astronomical Institute University of Bern (AIUB), Sidlerstrasse 5, 3012 Bern, Switzerland.
[‡] Professor, Astronomical Institute University of Bern (AIUB), Sidlerstrasse 5, 3012 Bern, Switzerland.
[§] Space Debris Engineer, ESA/ESOC, Robert-Bosch-Str 5, 64293 Darmstadt, Germany.
[**] Senior Space Debris Monitoring Analyst, ESA/ESOC, Robert-Bosch-Str 5, 64293 Darmstadt, Germany.

AAS 20-537

# MITRE TELESCOPE TRACKS BEPICOLOMBO FLYBY[*]

**Roger L. Mansfield[†] and Tim McLaughlin[‡]**

On April 10, 2020, the Mercury probe BepiColombo made a planned flyby of Earth. Earth provided, thereby, a gravity assist on this first of a sequence of BepiColombo gravity-assist flybys of planets Earth, Venus, and Mercury toward a goal that the spacecraft orbit Mercury in 2025. Using a custom flyby forecast prepared by registering at the *Heavens-Above* website, the authors obtained predictions of exactly when and where to look to acquire and track the spacecraft during its passage near Earth. This paper reports on the processes of planning, prediction, acquisition, tracking, measurement collection, and measurement reduction as needed to independently document the passage of the space probe by Earth, and to generate tracking data for testing of MITRE mission software under development.

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[*] Technical data produced for U.S. Government under Contract No. FA8702-19-C-0001 and subject to Rights in Technical Data-Noncommercial Items Clause DFARS 252.227-7013 (FEB 2014).



[†] Principal Astrodynamicist, The MITRE Corporation, Dept. P433, 1155 Academy Park Loop, Colorado Springs, CO 80910-3704 USA. Member, American Astronomical Society. Member, American Astronautical Society.

[‡] Principal Sensors Systems Engineer, The MITRE Corporation, Dept. P433, 1155 Academy Park Loop, Colorado Springs, CO 80910-3704, USA.

AAS 20-538

# VAN ALLEN PROBES END OF MISSION NAVIGATION AND MISSION DESIGN

**Ryan J. Bull,* Justin A. Atchison,† and Fazle E. Siddique‡**

NASA's twin Van Allen Probes spacecraft completed their extended mission and end-of-mission activities in mid-2019. Following the depletion of their propellant, each spacecraft continued operating for a month, during which the mission team carried out passivation activities. NASA policy requires that a satellite must reenter or be safely disposed of within 25 years of the mission's end. To meet this requirement, we designed and executed a series of maneuvers to lower perigee and eventually de-orbit the satellites using atmospheric drag. The satellites are in highly elliptical orbits, and the maneuvers decreased the perigee altitudes from roughly 600 km and 610 km to 260 km and 270 km for Van Allen Probes A and B, respectively. Our analysis indicates that these final altitudes have a high likelihood of satisfying the 25 year requirement, despite uncertainties in the long-term satellite attitudes. This paper describes that process and the outcome, including navigation challenges we encountered in the final low perigee orbits.

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* Associate Engineer, Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD 20723, USA.
† Senior Engineer, Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory.
‡ Senior Engineer, Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory.

AAS 20-544

# IMPROVING NAVIGATION ANALYSIS WITH OD-D: THE VISUALLY INTERACTIVE ORBIT DETERMINATION DASHBOARD*

James Crowley,† Isaac Mackey,‡ Jeffrey Stuart,§
Basak Alper Ramaswamy,** and Moriba Jah††

Robust orbit determination requires iterative multiple hypothesis analysis with the goal of using evidence to infer the most plausible states and model parameters regarding the behavior of an anthropogenic space object (a.k.a. a spacecraft) as possible, a process that can be both time and labor intensive. To increase the efficiency and accuracy of this analysis, we provide an analytic application capable of comprehensively and concurrently displaying multiple orbit determination solutions, leveraging contemporary data visualization techniques. This work details the design and visualization decisions made in the creation of the "Orbit Determination Dashboard," a tool aimed at giving users an interactive workspace for understanding how changes to input parameters defining the space environment, spacecraft features, sensor models and more affect their orbit determination solutions.

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† Graduate Research Assistant, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 110 Inner Campus Dr., Austin, TX 78705, USA.

‡ Graduate Student, Computer Science, University of California, Santa Barbara, 2104 Harold Frank Hall, Santa Barbara, CA, 93106, USA.

§ GNC Engineer, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, 91109, USA.

** Data Visualization Developer, Planning & Execution Systems Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, 91109, USA.

†† Associate Professor, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 110 Inner Campus Dr., Austin, TX 78705, USA. AAS and AIAA Fellow.

**AAS 20-555**

# MULTI-VARIATE GAUSSIAN PROCESS REGRESSION FOR ANGLES-ONLY INITIAL ORBIT DETERMINATION

**David Schwab,[*] Puneet Singla,[†] and Daning Huang[‡]**

Vital for Space Situational Awareness, initial orbit determination is used to initialize object tracking and associate observations with a tracked satellite. These classical IOD algorithms provide only a point solution and have been shown to be sensitive to noisy measurements and to certain target-observer geometry. In this work, a multivariate Gaussian process regression (GPR) is trained to perform angles-only orbit determination. This work extends the GPR approach to accurately quantify the orbit states along with associated covariance. The numerical simulations shows that by accounting for correlations in the outputs, the GPR process provides more accurate estimate of orbit uncertainty.

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[*] Graduate Student, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: dvs5558@psu.edu.

[†] Professor, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: psingla@psu.edu. AIAA Associate Fellow, AAS Fellow.

[‡] Assistant Professor, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: daning@psu.edu.

**AAS 20-586**

# A SEQUENTIAL MINIMUM L1-NORM ORBIT DETERMINATION ALGORITHM

**Kaushik Prabhu,[*] Manoranjan Majji,[†] and Kyle T. Alfriend[‡]**

An algorithm to update the minimum $L_1$-norm orbit estimate by sequentially processing new batches of measurements is presented. This sequential algorithm is based on the Dikin's interior point method to solve an $L_1$-norm minimization problem in linear models. Accuracy comparisons are made between the sequential least squares and the proposed algorithm for a representative orbit determination example.

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[*] PhD Student, Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
[†] Assistant Professor, Department of Aerospace Engineering, Texas A&M University.
[‡] TEES Eminent Research Professor, Department of Aerospace Engineering, Texas A&M University.

AAS 20-594

# OBSERVABILITY-AWARE NUMERICAL ALGORITHM FOR ANGLES-ONLY INITIAL RELATIVE ORBIT DETERMINATION

**Adam W. Koenig[*] and Simone D'Amico[†]**

This paper presents a simple numerical solution to the problem of estimating the relative orbit of a nearby resident space object using inertial bearing angle measurements from a single monocular camera. Unlike previous approaches, this algorithm provides a covariance for the computed state estimate, is robust to substantial errors in the a-priori state information, and is applicable to any planetary orbit regime as long as accurate models of dominant perturbations are available. This robust performance is enabled by three features of the proposed algorithm. First, leveraging the results of a quantitative observability analysis, the semimajor axis of the observer's orbit is estimated in addition to the relative orbit. Second, the weakly observable range is estimated through a sampling approach and the other strongly observable components are estimated using iterative batch least squares refinement. Third, the uncertainty in the a-priori information is included in the computation of the uncertainty for the estimated state. Monte Carlo simulations using a high-fidelity numerical orbit propagator are conducted to validate the performance of the algorithm and characterize its sensitivity to errors in the a-priori information in both earth and mars orbits. The simulation results show that the proposed algorithm provides relative orbit estimates that are at least as accurate as the best approaches in literature in a wider range of orbit regimes in the presence of larger errors.

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[*] Postdoctoral Scholar, Aeronautics & Astronautics Dept., Durand Building, 496 Lomita Mall, Stanford CA, 94305, USA.

[†] Assistant Professor, Aeronautics & Astronautics Dept., Durand Building, 496 Lomita Mall, Stanford CA, 94305, USA.

**AAS 20-610**

# GENERATIVE MODEL FOR SPACECRAFT IMAGE SYNTHESIS USING LIMITED DATASET

**Tae Ha Park[*] and Simone D'Amico[†]**

This work presents for the first time a conditional Generative Adversarial Network (GAN) to sample arbitrary high-fidelity spacecraft images from the learned distribution of spacecraft texture and illumination conditions (i.e., styles). The proposed SPEEDGAN utilizes a low-texture template of the spacecraft to empower SPEEDGAN with a priori knowledge of the spacecraft geometry and pose, allowing the model to focus on creating a spacecraft style. The SPEEDGAN also trains with a content loss from style transfer literature to improve the structural fidelity of the generated spacecraft images. Trained on a limited dataset containing images from the computer graphics renderer and the hardware-in-the-loop simulation facility, SPEEDGAN generates samples with remarkable visual qualities, measured by both human and a separate neural network for pose estimation. It is also capable of separated control over different style aspects, such as spacecraft texture and illumination effects.

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[*] Ph.D. Candidate, Department of Aeronautics & Astronautics, Stanford University, Stanford, CA 94305, USA.
[†] Assistant Professor, Department of Aeronautics & Astronautics, Stanford University, Stanford, CA 94305, USA.

AAS 20-613

# ORBIT DETERMINATION SIMULATION FOR KOREA PATHFINDER LUNAR ORBITER USING BALLISTIC LUNAR TRANSFER

**Young-Rok Kim,[*] Young-Joo Song,[†] Jae-ik Park,[‡] Donghun Lee,[§] Jonghee Bae,[**] SeungBum Hong,[††] Dae-Kwan Kim,[‡‡] and Sang-Ryool Lee[§§]**

The Korea Pathfinder Lunar Orbiter (KPLO) is Korea's first lunar exploration program developed by the Korea Aerospace Research Institute and will be launched in mid-2022. To reduce the ΔV for lunar capture, the trans-lunar trajectory of the KPLO was changed to one involving the low-energy ballistic lunar transfer (BLT) and weak stability boundary concepts. This study demonstrates the orbit determination (OD) and orbit prediction (OP) strategies and expected performances for the KPLO BLT trajectory including lunar orbit insertion (LOI) burns. The BLT translunar trajectory and LOI orbit of the KPLO are simulated using STK Astrogator. The range and Doppler tracking measurements of the KPLO are generated using the Orbit Determination Tool Kit, and two antennas of the Deep Space Network and the Korea Deep Space Antenna are considered for the ground tracking configuration. For the trans-lunar cruise phase before the first LOI burn, the OD and OP performances are investigated for stable execution of trajectory correction maneuvers (TCMs). For the lunar orbit approach phase, the OD and OP results are analyzed for LOI planning and execution. Sequential estimation is used for OD, and the position and velocity uncertainties are the main means of assessing the quality of the estimated orbit. Also checked are the differences between the estimated and true trajectories. To achieve the target conditions of the mission orbit successfully, the inclination uncertainty at the first LOI burn is also investigated. Finally, state error information is prepared to analyze the trajectory navigation errors and determine the TCM locations. The results are useful guidelines for the trajectory design and navigation analyses of the KPLO, including its TCM burn planning and trajectory error study.

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[*] Senior Researcher, KPLO Systems Engineering Team, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseonggu, Daejeon, 34133.
[†] Senior Researcher, KPLO Systems Engineering Team, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseonggu, Daejeon, 34133.
[‡] Senior Researcher, KPLO Systems Engineering Team, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseonggu, Daejeon, 34133.
[§] Senior Researcher, KPLO Systems Engineering Team, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseonggu, Daejeon, 34133.
[**] Senior Researcher, KPLO Systems Engineering Team, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseonggu, Daejeon, 34133.
[††] Senior Researcher, KPLO Systems Engineering Team, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseonggu, Daejeon, 34133.
[‡‡] Head, KPLO Systems Engineering Team, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon, 34133.
[§§] Director, Lunar Exploration Program Office, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon, 34133.

AAS 20-614

# IMAGE-BASED ATTITUDE DETERMINATION OF CO-ORBITING SATELLITES ENHANCED WITH DEEP LEARNING TECHNOLOGIES

**Ben Guthrie,* Minkwan Kim,† Hodei Urrutxua,‡ and Jonathon Hare§**

Active debris removal missions pose demanding guidance, navigation and control requirements. We present a novel approach which adopts deep learning technologies to the problem of attitude determination of an uncooperative debris satellite of a-priori unknown geometry. A siamese convolutional neural network is developed, which detects and tracks inherently useful landmarks from sensor data, after training upon synthetic datasets of visual, LiDAR or RGB-D data. The method is capable of real-time performance while significantly improving upon conventional computer vision-based approaches, and generalises well to previously unseen object geometries, enabling this approach to be a feasible solution for guidance in active debris removal missions. The performance of the algorithm and its sensitivity to model parameters are analysed via numerical simulation.

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* PhD Student, Aeronautics and Astronautics Department, University of Southampton, Southampton SO17 1BJ, United Kingdom.
† Lecturer, Aeronautics and Astronautics Department, University of Southampton, Southampton SO17 1BJ, United Kingdom.
‡ Lecturer, Aerospace Engineering, Universidad Rey Juan Carlos, 28943 Fuenlabrada, Madrid, Spain.
§ Associate Professor, Electronics and Computer Science Department, University of Southampton, Southampton SO17 1BJ, United Kingdom.

# INVESTIGATION OF IMPROVED ORBIT AND ATTITUDE ESTIMATION FROM SIMULTANEOUS DUAL-LATITUDE OBSERVATIONS

Zachary W. Henry,[*] Phillip R. Vavala,[†] David A. Zuehlke,[‡] Troy A. Henderson,[§] and John T. Grage[**]

This paper investigates utilizing dual-latitude optical measurements for improved orbit and attitude estimation of spacecraft. High-cadence optical measurements (i.e. images) are processed to reduce noise and maximize detection of Resident Space Objects (RSOs). A method of autonomously identifying RSOs in continuous imagery provides angular measurements to an Extended Kalman Filter to perform orbit estimation. Simulated angular observations are used to verify the algorithm. Finally, simulated light curve data is compared to actual light curve data gathered on a Geostationary satellite.

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[*] Master's Student, Aerospace Engineering, Embry-Riddle Aeronautical University, 1 Aerospace Blvd., Daytona Beach, Florida 32114, USA.
[†] Master's Student, Aerospace Engineering, Embry-Riddle Aeronautical University, 1 Aerospace Blvd., Daytona Beach, Florida 32114, USA.
[‡] Ph.D. Student, Aerospace Engineering, Embry-Riddle Aeronautical University, 1 Aerospace Blvd., Daytona Beach, Florida 32114, USA.
[§] Associate Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, 1 Aerospace Blvd., Daytona Beach, Florida 32114, USA.
[**] Mind's Eye Observatory, Sebastian, Florida, USA.

AAS 20-696

# INITIAL RELATIVE-ORBIT DETERMINATION OF SPACE OBJECTS VIA RADIO FREQUENCY SIGNAL LOCALIZATION

**Troy A. Henderson,* Yasmeen Hack,† Sophia Sunkin,‡ T. Alan Lovell,§ Joshuah Hess,** and Jessica Wightman††**

This paper presents a solution method for the initial orbit determination of a space-based transmitter using radio frequency measurements obtained from space-based receivers. Initial orbit determination requires a minimum of six independent measurements over time. Many radio frequency-based measurement equations can be expressed in polynomial form. The orbital motion of the transmitter is linearized relative to a reference orbit, which allows each radio frequency measurement to be expressed as a polynomial equation for the relative position and velocity of the transmitter at a chosen epoch time. The system of polynomials is then solved using known applied mathematics techniques.

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* Associate Professor, Aerospace Engineering, Embry-Riddle Aeronauical University, 1 Aerospace Blvd., Daytona Beach, FL 32174, USA.
† Undergraduate Student, Department of Mathematics, Colorado State University, Fort Collins, CO 80523, USA.
‡ Student, Mission Viejo High School, Mission Viejo, CA 92691, USA.
§ Senior Aerospace Engineer, Air Force Research Laboratory, Kirtland AFB, NM 87117, USA.
** Assistant Professor, Aerospace Engineering, Air Force Institute of Technology, Dayton, OH 45433, USA.
†† Graduate Student, Aerospace Engineering, Air Force Institute of Technology, Dayton, OH 45433, USA.

AAS 20-734

# NEURAL NETWORK BASED TLE ERROR MODELING AND QUANTIFICATION

**Nathan Reiland,[*] Simon Jaxy,[†] Di Wu,[‡] and Aaron J. Rosengren[§]**

This paper proposes a neural network based method for TLE (Two-Line Element) data error modeling. The complicated mapping between TLE error and a satellite's position and velocity is largely unknown due to the lack of data driven techniques that are effective when applied to complex, nonlinear dynamical systems. For this study, the passive MEO (medium Earth orbit) satellites, Lageos 1 and Lageos 2 are considered. Their high accuracy satellite laser ranging (SLR) based ephemeris from the ILRS (international laser ranging service) is compared with corresponding TLE data to create a dataset for the neural network's training and validation. The results of this work illustrate the possibility of utilizing neural networks to estimate TLE error information, thereby improving the usability of TLEs for SSA applications.

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[*] Systems Engineer, Raytheon Missiles and Defense, Tucson, Arizona 85756, USA.
[†] BSc., Artificial Intelligence Department, Vrije Universiteit Brussels, B-1050 Brussels, Belgium.
[‡] Graduate Student, Aerospace and Mechanical Engineering Department, University of Arizona, Tucson, AZ 85719, USA.
[§] Assistant Professor, Department of Mechanical and Aerospace Engineering, University of California San Diego, 92093, USA.

**AAS 20-777**

# SEQUENTIAL ORBIT DETERMINATION VERIFICATION FOR GEOSTATIONARY SATELLITES

**Abdulkadir Köker,[*] Ozan Tekinalp,[†] Ü. Cezmi Yılmaz,[‡] and Cemal Şakacı[§]**

Sequential orbit determination using angle and range measurements for geostationary satellites is presented. The approach includes position, velocity and bias estimation with Unscented Kalman Filter. The measurements are taken from the actual ground station antennas at TURKSAT. In order to evaluate the accuracy and the robustness of the system, estimation is repeated with single and multiple ground station measurements for satellite T4B. Estimation results are compared with the reference orbit determination software and a very good agreement is obtained.

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[*] Senior Researcher, Aerospace Engineering Department, TUBITAK Space Tech. Research. Inst., Ankara, Turkey. E-mail: kokabdul@hotmail.com.
[†] Professor, Aerospace Engineering Department, Middle East Technical University, Ankara, Turkey. E-mail: tekinalp@metu.edu.tr.
[‡] Director, TURKSAT Satellite Control Center, Ankara, Turkey. E-mail: cyilmaz@turksat.com.tr.
[§] Flight Dynamics Expert, TURKSAT Satellite Control Center, Ankara, Turkey. E-mail: csakaci@turksat.com.tr.

# ORBITAL DYNAMICS,
# PERTURBATIONS, AND STABILITY

AAS 20-410

# LINEAR GROWTH IN ECCENTRICITY AT CRITICAL INCLINATION—A THEORETICAL INVESTIGATION

**Chia-Chun George Chao***

The concept of the frozen orbit has been well understood through the equations due to $J_2$ and $J_3$ perturbations. An orbit at critical inclination is considered one type of frozen orbit. However, a low Earth orbit at critical inclination will have a slow linear growth in eccentricity due to higher-order odd zonal harmonics ($J_5$, $J_7$, $J_9$,…). This paper presents a theoretical investigation through derivations based on Kaula's F and G functions. The resulting series solutions for de/dt and dω/dt can be reduced to simple forms which compared well with numerical integration. The coupling between the two equations reveals an interesting property that the linear growth in eccentricity is independent of initial argument of perigee values.

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* Retired engineer, former employee of The Aerospace Corporation and Jet Propulsion Laboratory, 21 Azulado Drive, Rancho Mission Viejo, CA 92694, USA. E-mail: chiachunchao@gmail.com. Tel. 949 443-8531. AIAA Fellow.

**AAS 20-413**

# LEO CONSTELLATIONS TO MINIMIZE GLOBAL MAX REVISIT TIME

**Thomas J. Lang***

For many applications, continuous coverage of the globe is not required. Instead, the mission designer may require that the maximum coverage gap to any point on the ground never exceed a specified duration. This maximum gap is generally referred to as the maximum revisit time (MRT). Allowing even a small MRT can substantially reduce the required constellation size. In the past, finding an optimal LEO constellation to achieve a specified MRT was an extremely difficult chore. This paper uses normalized values of MRT (normalized by the orbit period) and "regular" constellations of circular orbit satellites to greatly simplify the problem. Optimized LEO constellations of 3 to 25 satellites have been computed and are presented in the tables of the Appendices. These tables allow a user to find the best constellation at any LEO altitude for a specified coverage circle size and a desired value of global MRT. A tool, which leverages these tables, displays the entire trade-space of constellation altitude, constellation size and MRT given only the minimum elevation angle requirement of the sensor. Polar and retrograde inclinations have been examined. Examples are presented to illustrate how the tables and plots can be used to quickly and easily find a LEO constellation at any altitude optimized to meet global MRT requirements.

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* Member of the Technical Staff, Retired, Astrodynamics Department, PO Box 92957 (MS: M4-948), Los Angeles, CA 90009-2957, USA.

**AAS 20-454**

# FORMATIONS WITH FROZEN RELATIVE ORBITS IN THE PRESENCE OF STRONG SOLAR RADIATION PRESSURE

**Alex J. Meyer* and Daniel J. Scheeres†**

Despite the many benefits of utilizing distributed space missions, controlling multiple spacecraft can be difficult in environments where perturbations are significant. Around small bodies such as asteroids, solar radiation pressure causes orbits to evolve over time, destroying formations of multiple orbits. Counteracting this effect requires the active control of spacecraft unless particular initial conditions are selected for the orbits. The vectoral Milankovitch elements provide a convenient and non-singular approach to modeling spacecraft dynamics around small bodies and can be used to solve for conditions in which formations of orbits evolve together. This creates so-called frozen relative orbits, where orbits remain coupled together despite perturbations from solar radiation pressure. A convenient geometric analysis emerges from the dynamic equations describing the evolution of Milankovitch vectors. From the geometry it becomes apparent that a set of arbitrary initial conditions for an orbit has three non-trivial corresponding frozen relative orbits.

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* Graduate Research Assistant, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder, CO 80303, USA.
† A. Richard Seebass Endowed Chair Professor, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 3775 Discovery Dr., Boulder, CO 80303, USA.

AAS 20-461

# EFFECT OF ATMOSPHERIC AND CELESTIAL PERTURBATIONS ON FLIGHT DYNAMICS DURING ORBITAL DECAY OF THE EGG NANOSATELLITE

**Maximilien Berthet[*] and Kojiro Suzuki[†]**

The EGG nanosatellite was launched from the ISS in 2017. EGG had no means of active attitude control, and deployed an inflatable drag-enhancing aeroshell to speed up atmospheric entry. Contrary to expectations, EGG experienced relatively long orbital decay (118 days) and energetic spin motion (>100 deg/s). In a previous coupled simulation study, which considered only atmospheric drag and Earth oblateness effects, the authors found discrepancies between the numerical results and experimental flight data. This suggested that additional perturbations had a measurable effect on flight of EGG. The main objective of this study is to evaluate the impact of a more comprehensive range of atmospheric and celestial perturbations in LEO on the flight dynamics. The analysis is performed via an in-house orbit-attitude simulation platform, which includes all force and torque perturbations acting on high area-to-mass ratio satellites in LEO to order $10^{-7}$ m/s$^2$ and $10^{-8}$ N.m respectively. The three key findings are that: (i) higher order geopotential acceleration played an important role in the evolution of orbital elements of EGG; (ii) coupling between attitude, aerodynamics, and magnetic torques induced by current loops in the rear-attached solar panels was the main contributor to energetic spin motion; and (iii) flat spin motion was responsible for the long flight duration.

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[*] PhD Student, Dept. of Aero. and Astro., Graduate School of Engineering, The University of Tokyo, Tokyo, Japan.
[†] Professor, Dept. of Advanced Energy, Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Japan.

AAS 20-469

# USING PRODUCTS OF EXPONENTIALS TO DEFINE (DRAW) ORBITS AND MORE

**Aryslan Malik,* Troy Henderson,† and Richard Prazenica‡**

The Product of Exponentials (PoE) formula is a mathematical tool that is used extensively in robotics. The virtue of using the exponential mapping, Lie Algebra and screw theory is that it allows an elegant and concise way of describing the orientation and position of a body with respect to another body in a multi-body system. Although the PoE formula is mainly used in robotics, this work aims to demonstrate the utility of the PoE formula as an alternative method for defining and drawing orbits given an orbital elements set. The work also explores the first derivative of the adapted PoE formula in the framework of orbital mechanics, which allows obtaining the state of the satellite (position and velocity) from the orbital elements set using the developed formulation.

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* Ph. D. Candidate, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA.
† Assistant Professor, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA.
‡ Associate Professor, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA.

AAS 20-476

# DEVELOPMENT AND ANALYSIS OF THE DOUBLY AVERAGED MODEL FOR SOLAR RADIATION PRESSURE

**Marielle M. Pellegrino,* Daniel J. Scheeres,† and Brett J. Streetman‡**

This paper investigates the formulation of the doubly averaged solar radiation pressure (SRP) perturbation. Doubly averaged dynamics can rapidly calculate the long term dynamics of a region. For space debris, these objects are often high area to mass ratio objects and are largely affected by solar radiation pressure. This paper will utilize existing models of singly averaged solar radiation pressure and double formulations to correctly model the growth in eccentricity due to SRP in terms of doubly averaged dynamics. The paper will also describe how accurately doubly averaged techniques can be used in studying regions of chaos.

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* Draper Fellow PhD Candidate, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder CO 80309, USA.

† A. Richard Seabass Chair Professor, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder CO 80309, USA.

‡ Principal Member of the Technical Staff, The Charles Stark Draper Laboratory, Inc., 555 Technology Square, Cambridge, MA 02139, USA.

AAS 20-479

# TLE DATA FROM THE EGG NANOSATELLITE MISSION AS A RESOURCE TO REVERSE ENGINEER PERTURBATIONS IN THE LEO ORBITAL DECAY ENVIRONMENT

**Maximilien Berthet* and Kojiro Suzuki†**

The two leading perturbations acting on satellites in the orbital decay region of low Earth orbit (LEO) are gravitational non-sphericity of the Earth and atmospheric drag. A detailed understanding of these perturbations is required to accurately predict satellite dynamics, such as the orbital lifetime. On the other hand, there is still room to improve current perturbation models in the orbital decay region, especially for atmospheric winds and composition. In this paper, two-line elements (TLEs) from the 2017 EGG nanosatellite mission are used to reverse engineer perturbations in the LEO environment. Due to the low ballistic coefficient of EGG and its low orbital altitude, flight was highly affected by both aerodynamic and geopotential effects. The objectives are: (i) to determine which perturbations can be detected in the flight data, and (ii) to use the flight data to obtain quantitative estimates of the perturbations. Secular and long-periodic atmospheric and geopotential perturbations are extracted via linearized perturbation theory. The results show that EGG acted as a low-cost passive sensor for multiple perturbations, including the changing solar flux, diurnal atmospheric bulge effects, rotating atmospheric winds, and the zonal geopotential. For example, the second zonal geopotential harmonic is estimated to within 0.008%.

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* PhD Student, Dept. of Aero. and Astro., Graduate School of Engineering, The University of Tokyo, Tokyo, Japan.
† Professor, Dept. of Advanced Energy, Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Japan.

**AAS 20-481**

# HIGH-FIDELITY MODELING AND VISUALIZING OF SOLAR RADIATION PRESSURE: A FRAMEWORK FOR HIGH-FIDELITY ANALYSIS

**Leandro Zardaín,* Ariadna Farrés,† and Anna Puig‡**

Solar Radiation Pressure (SRP) is the force produced by the impact of sunlight photons on the surface of the spacecraft. This extra force, despite being small, plays an important role on trajectory design and orbit determination. In this paper we present an open-source tool that enables the user to compute high-fidelity approximations of SRP accelerations for a given spacecraft using ray-tracing techniques. The tool also allows the user to compare between different fidelity levels and different models like the N-plate or the cannonball finding a trade-off on the SRP accuracy between computation time and accuracy.

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* Student, Universitat Politecnica de Catalunya, Carrer de Jordi Girona 1, Barcelona, Spain. E-mail: leandrozardain@gmail.com.
† Dr., NASA/Goddard Space Flight Center, University of Maryland Baltimore County. 1000 Hilltop Circle, Baltimore, MD 21250, USA. E-mail: ariadna.farresbasiana@nasa.gov.
‡ Prof., Universitat de Barcelona, Gran Via de les Corts Catalanes 585, Barcelona, Spain. E-mail: annapuig@ub.edu.

AAS 20-488

# MOTION PRIMITIVES SUMMARIZING PERIODIC ORBITS AND NATURAL TRANSPORT MECHANISMS IN THE EARTH-MOON SYSTEM

Thomas R. Smith* and Natasha Bosanac†

Rapid trajectory design in multi-body systems often leverages individual arcs along natural dynamical structures that exist in an approximate dynamical model. To reduce the complexity of analysis during this process, motion primitives are constructed as a set of arcs that represent the finite geometry, stability, and energy characteristics exhibited by a family of trajectories. In the absence of generalizable analytical criteria for extracting these representative solutions, clustering is employed. In this paper, this clustering-based approach to constructing motion primitives is improved and applied to spatial periodic orbit families and hyperbolic invariant manifolds in the Earth-Moon circular restricted three-body problem.

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* Graduate Research Assistant, Colorado Center for Astrodynamics Research, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80303, USA.
† Assistant Professor, Colorado Center for Astrodynamics Research, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80303, USA.

# SEMI-ANALYTIC SOLUTIONS TO THE HAMILTON-JACOBI EQUATION WITH APPLICATIONS TO ORBIT PROPAGATION IN PERTURBED TWO-BODY REGIMES

**Roshan T. Eapen,[*] Manoranjan Majji,[†] Kyle T. Alfriend,[‡] and Puneet Singla[§]**

A systematic numerical approach to solve the Hamilton-Jacobi partial differential equation is proposed in this paper. Advances in sparse collocation methods are utilized to develop an algorithm to obtain an approximate functional form for the generating function. By employing a family of trajectories in the domain of the relevant phase volume, the generating function is formulated that governs the transformation of coordinates to rectify the motion of a dynamical system. The utility of this method is demonstrated by obtaining a semi-analytic solution to the main problem in artificial satellite theory.

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[*] Ph.D. Candidate, Department of Aerospace Engineering, Texas A&M University, College Station TX 77843-3141, USA.
[†] Assistant Professor, Department of Aerospace Engineering, Texas A&M University.
[‡] TEES Distinguished Research Professor, Department of Aerospace Engineering, Texas A&M University.
[§] Associate Professor, Department of Aerospace Engineering, Pennsylvania State University, State College, PA 16802, USA.

AAS 20-542

# KING-HELE ORBIT THEORY FOR PERIODIC ORBIT AND ATTITUDE VARIATIONS

Vishal Ray* and Daniel J. Scheeres†

The analytical theory of satellite orbits in an atmosphere developed by King-Hele remains widely in use for satellite mission design because of its accurate approximation to numerical integration under simplifying assumptions. Over the course of six decades, modifications to the theory have addressed many of its weaknesses. However, in all subsequent modifications of the original theory, the assumption of a constant drag-coefficient has been retained. The drag-coefficient is a dynamic parameter that governs the physical interaction between the atmosphere and the satellite and depends on ambient as well as satellite specific factors. In this work, Fourier series expansion models of the drag-coefficient are incorporated in the original King-Hele theory to capture the time-variation of the drag-coefficient in the averaging integrals. The modified theory is validated through simulations that demonstrate the attained improvements in approximating numerical results over the original King-Hele formulation.

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* Graduate Research Assistant, Ann and H.J Smead Aerospace Engineering Sciences, University of Colorado Boulder, CO 80309, USA.
† A. Richard Seebass Endowed Professor, Ann and H.J Smead Aerospace Engineering Sciences, University of Colorado Boulder, CO 80309, USA. Fellow AIAA.

**AAS 20-571**

# USING ARTIFICIAL NEURAL NETWORKS FOR OFFLINE GRAVIMETRY

**J. R. Martin[*] and H. Schaub[†]**

Resolving a reliable, high-fidelity mapping between position and gravitational acceleration is paramount for accurate trajectory design and mission planning. These mappings are typically constructed through complex formulations that include large spherical harmonic expansions or polyhedral models that require thousands of facets. Such models are expensive to compute, difficult to extract, and demand particular assumptions of the gravitational environment or operational conditions of the effected spacecraft. Recent literature suggests that artificial neural networks may be capable of circumventing such limitations – however it is unclear if such networks can model the dominant, surface level perturbations. This paper attempts to fill that hole, looking specifically at how well these networks can model perturbations beyond $J_2$.

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[*] NSF Graduate Research Fellow, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, CO 80309, USA.
[†] Glenn L. Murphy Chair of Engineering, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, CO 80309, USA. AAS Fellow, AIAA Fellow.

# SECULAR EVOLUTION OF THE MOID FOR NEAR-EARTH OBJECTS

**Oscar Fuentes-Munoz[*] and Daniel J. Scheeres[†]**

The Minimum Orbit Intersection Distance (MOID) is a metric that bounds the closest fly-bys between celestial bodies. Understanding the long-term evolution of the MOID we can assess collision risks and study the recent history of asteroids in the inner solar system. The dynamics of the MOID are described using a secular model for the Solar System and numerical integrations. A variety of orbits in the Near-Earth space are investigated to find how often NEO trajectories fit the secular model.

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[*] Research Assistant, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, CO 80303-0429, USA.

[†] University of Colorado Distinguished Professor, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, CO 80303-0429, USA.

AAS 20-588

# TRANSFERS BETWEEN INTERSECTING QUASI-PERIODIC TORI

**Damennick B. Henry[*] and Daniel J. Scheeres[†]**

Over the past decade, missions which exploit dynamical features of the Earth-Moon system have garnered significant interest. The most abundant feature in these three-body systems are quasi-periodic tori (QPTs), making them prime candidates for mission operations. In this work, transfers between QPTs which intersect in position space will be investigated. To this end, a methodology for determining where a pair of QPTs intersect and the maneuver that would allow for a transfer between them has been developed. These constraints motivated a predictor-corrector algorithm for computing the continuum of points where these multi-dimensional objects intersect. This numerical procedure has been used to identify intersecting trajectories on Lissajous and quasi-halo orbits, allowing for a single impulsive maneuver to be used to transfer between them.

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[*] Graduate Research Assistant, Department of Aerospace Engineering Sciences, UCB, Boulder, CO 80309, USA.
[†] A. Richard Seebass Chair Professor, Department of Aerospace Engineering Sciences, 429 UCB, Boulder, CO 80309, USA.

AAS 20-621

# A HIGH-ORDER TAYLOR POLYNOMIALS APPROACH FOR CONTINUING TRAJECTORIES IN RESTRICTED THREE-BODY PROBLEMS

**Nicola Baresi,[*] Xiaoyu Fu,[†] and Roberto Armellin[‡]**

Space exploration has often benefitted from the qualitative analyses of non integrable problems enabled by numerical continuation procedures. Yet, standard approaches based on Newton's method typically end with discrete representations of family branches that may be subject to misinterpretation and overlook important dynamical features. In this research, we introduce novel continuation procedures based on the differential algebra of Taylor polynomials. Our algorithms aim at generating dense family branches as an atlas of polynomial charts that are locally valid for a range of system and continuation parameters. Examples of particular solutions will be shown within the framework of the Circular Restricted Three-Body Problem, along with fold and period-doubling bifurcations that are efficiently detected using automatic domain splitting and map inversion techniques.

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[*] Lecturer, Surrey Space Centre, University of Surrey, GU2 7XH, Guildford, UK.
[†] PhD Candidate, Surrey Space Centre, University of Surrey, GU2 7XH, Guildford, UK.
[‡] Full Professor of Space Systems Department of Aerospace Vehicles Design and Control - DCAS Institut Supérieur de l'Aeronautique et de l'Espace (ISAE-SUPAERO) 10, avenue Edouard Belin - BP 54032 31055 Toulouse Cedex 4 France.

**AAS 20-654**

# APPLICATION OF UDWADIA-KALABA FORMULATION TO THE PLANAR ELLIPTICAL RESTRICTED THREE-BODY PROBLEM

**Harshkumar Patel,[*] Hancheol Cho,[†] Morad Nazari,[‡] and Troy A. Henderson[§]**

This paper introduces the Udwadia-Kalaba (UK) formulation of constrained dynamics as applied to the planar elliptical restricted three-body problem (Sun-Earth-spacecraft). The unconstrained motion of the spacecraft is analyzed under the gravitational influences of the Sun and the Earth, where the Earth is in its elliptical orbit around the Sun. In addition, solar radiation pressure is applied to the spacecraft. The results verify a drift from the Lagrange point. Then, the UK formulation is applied to derive the equation of motion of the spacecraft by adding the constraints such that the spacecraft remains exactly at the Lagrange point with respect to the Sun and the Earth. Exact amount of thrust with the directions is obtained to stay at the Lagrange points L1 and L4. The Baumgarte's stabilization method is included to consider the case when the spacecraft is inserted away from the Lagrange point initially. In this case, the results are analyzed for the underdamped, overdamped and critically-damped cases. In addition, the $\Delta V$ is compared for the transient response with the time-varying linear quadratic regulator (LQR) where the optimal feedback control gains are designed via the periodic Riccati equation. The control accelerations required to maintain the desired position obtained by the UK technique are obtained to be identical to those obtained via using the feedforward part of the time-varying LQR control, as expected.

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[*] Graduate Student, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd, Daytona Beach, FL 32114, USA. E-mail: patelh20@my.erau.edu.
[†] Assistant Professor, Department of Mechanical Engineering, Bradley University, Peoria, IL 60607, USA.
[‡] Assistant Professor, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL.
[§] Associate Professor, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL.

# AAS 20-684

# EXAMINATION OF SPIN-ORBIT RESONANCE IN ECCENTRIC AND LOW ALTITUDE MARS ORBITS

**Andres Dono,[*] Laura Plice,[†] Jose Alvarellos,[*] Ted Hendriks,[‡] and Ron L. Evans[§]**

Low orbit perturbations derive from mass concentrations and show high sensitivity to certain initial orbit parameters and spin-orbit resonance conditions. Evaluation of spin-orbit resonance and gravity perturbation effects are important in mission design applications. Here we examine low altitude and polar orbits of Mars. The method uses analytical derivations to identify regimes of interest and computational modeling and graphical design aids for detailed investigation.

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[*] Flight Dynamics Analyst, Millennium Engineering and Integration Services NASA Ames Research Center, Moffett Field, Mountain View, CA 94035, USA.
[†] Flight Dynamics Lead, Metis Technology Solutions, NASA/Ames Research Center, Mission Design Center, Moffett Field, Mountain View, CA 94035, USA.
[‡] Flight Dynamics Analyst, Metis Technology Solutions, NASA/Ames Research Center, Mission Design Center, Moffett Field, Mountain View, CA 94035, USA.
[§] Flight Dynamics Programmer, Millennium Engineering and Integration Services NASA Ames Research Center, Moffett Field, Mountain View, CA 94035, USA.

AAS 20-685

# DYNAMICS OF ORBITS NEAR 4:1 LUNAR RESONANCE

**Stephen West,[*] John Carrico,[†] Andres Dono,[‡] Andrew Koehler,[§] Paul Levinson-Muth,[**] Dylan Morrison Fogel,[††] and Laura Plice[‡‡]**

Periodic orbits near 4:1 lunar resonance provide long-term stability for missions requiring high apogee altitudes. The planar family of 4:1 resonant orbits are stable with two quasi-periodic modes: a slow out of plane mode with a period approaching 25 years and a fast in-plane mode with a period approaching 1 year. We analyze these orbits in the circular restricted three-body problem and compare the results with long-term propagations in a high fidelity ephemeris model.

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[*] Flight Dynamics Analyst, Metis Technology Solutions, NASA Ames Research Center, Moffett Field, CA 94035, USA. E-mail: stephen.t.west@nasa.gov.
[†] CTO, Astrogator, & Technical Advisor, Space Exploration Engineering, 324 Main Street #173, Laurel, MD 20725-0173, USA.
[‡] Flight Dynamics Analyst, Millennium Engineering and Integration Services, NASA Ames Research Center, Moffett Field, CA 94035, USA.
[§] Student Trainee, NASA Ames Research Center, Moffett Field, CA 94035, USA.
[**] Flight Dynamics Intern, Millennium Engineering and Integration Services, NASA Ames Research Center, Moffett Field, CA 94035, USA.
[††] Flight Dynamics Intern, Millennium Engineering and Integration Services, NASA Ames Research Center, Moffett Field, CA 94035, USA.
[‡‡] Flight Dynamics Lead, Metis Technology Solutions, NASA Ames Research Center, Moffett Field, CA 94035, USA.

**AAS 20-691**

# MINIMIZING CLOSURE ERROR OF REPEATING GROUND TRACK ORBITS FOR HURRICANE MONITORING CUBESAT CONSTELLATION

**Pardhasai Chadalavada* and Atri Dutta†**

Regional constellations using a network of CubeSats can be useful in monitoring large-scale weather events such as hurricanes. For such applications, the design of repeating ground track orbits usually leads to a fewer number of CubeSats. In this paper, we propose a optimization based approach for the design of repeating ground track orbits, by minimizing the ground track closure error. We demonstrate the methodology using numerical simulation of different low-Earth orbits and comparing the associated ground track errors.

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* Ph.D. Student, Aerospace Engineering, Wichita State University, 1845 Fairmount St Box 42, Wichita KS 67260, USA.

† Assistant Professor, Aerospace Engineering, Wichita State University, 1845 Fairmount St Box 42, Wichita KS 67260, USA.

AAS 20-694

# RAPID AND ACCURATE COMPUTATION OF INVARIANT TORI, MANIFOLDS, AND CONNECTIONS NEAR MEAN MOTION RESONANCES IN PERIODICALLY PERTURBED PLANAR CIRCULAR RESTRICTED 3-BODY PROBLEM MODELS

**Bhanu Kumar,[*] Rodney L. Anderson,[†] and Rafael de la Llave[‡]**

When the planar circular restricted 3-body problem (RTBP) is periodically perturbed, most unstable resonant periodic orbits become invariant tori. In this study, we 1) develop a quasi-Newton method which simultaneously solves for the tori and their center, stable, and unstable directions; 2) implement continuation by both perturbation as well as rotation numbers; 3) compute Fourier-Taylor parameterizations of the stable and unstable manifolds; 4) globalize these manifolds; 5) compute homoclinic and heteroclinic connections. Our methodology improves on efficiency and accuracy compared to prior studies, and applies to a variety of periodic perturbations. We demonstrate the tools on the planar elliptic RTBP.

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[*] PhD Candidate, School of Mathematics, Georgia Institute of Technology, 686 Cherry St. NW, Atlanta, GA 30332, USA.

[†] Technologist, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

[‡] Professor, School of Mathematics, Georgia Institute of Technology, 686 Cherry St. NW, Atlanta, GA 30332, USA.

AAS 20-704

# PERTURBED TROJAN DYNAMICS IN THE SOLAR SYSTEM

**Ram Krishan Sharma,[*] Harishkumar Sellamuthu,[†] and Arantza Jency[‡]**

Perturbed elliptical restricted three-body problem has been studied with an analytically derived mean motion expression. The expression and the value of the mean motion is found to be different from the previous studies but aligns with the laws of orbital motion. The distance shift of the first five Lagrangian points for several systems of astronomical importance is observed and the linear stability is discussed. We have found that, for eccentricity > ~0.6447, the range of mass parameter providing linearly stable solutions at the triangular points increases. The Trojan motion of objects in the Sun-Jupiter and other systems have been studied.

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[*] Professor, Department of Aerospace Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India.
[†] Astrodynamics researcher, Agnikul Cosmos Private Limited, Indian Institute of Technology Madras, Chennai, India.
[‡] Undergraduate Student, Department of Aerospace Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India.

AAS 20-706

# DIRECT EXPLORATION OF THE $L_2$ ISOLATED INVARIANT SET USING ISOLATING NEIGHBORHOODS*

Rodney L. Anderson,† Robert W. Easton,‡ and Martin W. Lo†

Previous studies have used isolating blocks to explore the isolated invariant set around the $L_2$ Lagrange point in the circular restricted three-body problem by computing trajectories on the asymptotic set and using them to track particular orbits. Once an initial map of the location of the orbits within the isolated invariant set projected into configuration space has been found, it is possible to further explore these orbits more directly by starting from appropriately chosen points within the mapped space. Here, we develop a method that uses these points to explore the periodic and quasiperiodic orbits within the isolated invariant set.

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† Technologist, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, M/S 301-121, Pasadena, CA 91109, USA.

‡ Professor Emeritus, Applied Mathematics, University of Colorado at Boulder, Boulder, CO 80309, USA.

**AAS 20-719**

# ORBITAL RENDEZVOUS AND SPACECRAFT LOITERING IN THE EARTH-MOON SYSTEM

**Fouad Khoury[*] and Kathleen C. Howell[†]**

To meet the challenges posed by future space exploration activities, relative satellite motion techniques and capabilities require development to incorporate dynamically complex regimes. In this investigation, relative motion in the restricted 3-body problem is formulated, validated, and tested to produce solutions to rendezvous and space loitering problems in the Earth-Moon system. Numerical techniques including targeting algorithms are explored to generate relative trajectories between two spacecraft in a 9:2 $L_2$ Near Rectilinear Halo Orbit (NRHO) as well as spacecraft in a large Distant Retrograde Orbit (DRO).

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[*] M.S. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: fkhoury@purdue.edu.

[†] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: howell@purdue.edu.

**AAS 20-722**

# ON THE SOLUTION OF THE FOKKER-PLANCK EQUATION WITHOUT DIFFUSION FOR UNCERTAINTY PROPAGATION IN ORBITAL DYNAMICS

**Giacomo Acciarini,[*] Cristian Greco,[†] and Massimiliano Vasile[‡]**

This paper presents a method to transform the Fokker-Planck partial differential equation without diffusion into a set of linear ordinary differential equations. This is achieved by first representing the probability density function (pdf) through a summation of time-varying coefficients and spatial basis functions and by then employing Galerkin projection in the Fokker-Planck equation. We show that this method, compared to other numerical techniques, can bring several advantages in the field of uncertainty propagation in orbital dynamics, by not only allowing to retain the entire shape of the pdf through time but also to very rapidly compute the pdf at any time and with any initial condition, once that the spatial support is chosen and several time-independent integrals on the chosen support are computed.

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[*] PhD Candidate, Aerospace Center of Excellence, University of Strathclyde, UK.
E-mail: giacomo.acciarini@strath.ac.uk.
[†] PhD Candidate, Aerospace Center of Excellence, University of Strathclyde, UK. E-mail: c.greco@strath.ac.uk.
[‡] Professor, Aerospace Center of Excellence, University of Strathclyde, UK. E-mail: massimiliano.vasile@strath.ac.uk.

# RENDEZVOUS, RELATIVE MOTION, PROXIMITY MISSIONS AND FORMATION FLYING

# ASSESSMENT OF THE DEPENDENCIES OF REALISTIC DIFFERENTIAL DRAG CONTROLLED IN-PLANE RECONFIGURATION MANEUVERS ON RELEVANT PARAMETERS

**Constantin Traub,[*] Stefanos Fasoulas,[†] and Georg H. Herdrich[‡]**

Differential drag is a promising option to control the in-plane relative motion of satellites which are not equipped with dedicated thrusting devices. In this paper, a powerful optimal control approach is used to design a differential drag-based in-plane re-phasing maneuver of two cooperative 3U CubeSats while minimizing the decay during the maneuver at the same time. The maneuver sequence is validated using a high-fidelity six degrees of freedom propagator. In a second step, a case study is performed in which the influence of the available differential drag force on the maneuver outcome is analyzed. The results suggest that, for a given satellite geometry, achieving high control forces and low values of orbital decay are opposing goals. Thus, the common opinion according to which satellites with low ballistic coefficients are beneficial for differential drag based formation control might be too short-sighted as this is only true in terms of the available control authority and the achievable maneuver times. Whereas the resulting maneuver time of differential drag controlled formations is frequently of secondary importance, orbital decay is irreversible and strongly affects the overall mission lifetime. Consequently, increasing the ballistic coefficients of the satellites to find an optimal trade-off between the available control authority, the maneuver time and the resulting orbital decay is proposed to increase the practicability and sustainability of the method.

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[*] M.Sc., Institute of Space Systems, University of Stuttgart, PhD candidate, Pfaffenwaldring 29, 70569 Stuttgart, Germany.

[†] Prof. Dr.-Ing., Institute of Space Systems, University of Stuttgart, Institute Director, Pfaffenwaldring 29, 70569 Stuttgart, Germany.

[‡] Priv.-Doz. Dr.-Ing., Institute of Space Systems, University of Stuttgart, Head Plasma Wind Tunnels and Electric Space Propulsion, Pfaffenwaldring 29, 70569 Stuttgart, Germany.

AAS 20-408

# PROGRESS IN SATELLITE FORMATION FLIGHT CONTROL USING DIFFERENTIAL AERODYNAMIC FORCES MADE AT THE INSTITUTE OF SPACE SYSTEMS (IRS)

**Constantin Traub,* Stefanos Fasoulas,† and Georg H. Herdrich‡**

This paper gives a comprehensive summary of the progress in the field of satellite formation flight control via differential aerodynamic forces made at the Institute of Space Systems of the University of Stuttgart. The research effort consists of two different approaches which are followed in parallel, namely 1.) the development and enhancement of simplified maneuver algorithms as well as 2.) the development of robust and highly detailed maneuver sequences, and which highly complement each other. The summary predominantly comprises already published results, but is supplemented by unpublished results in both fields accomplished during the last months. Based on the progress achieved so far, conclusions are drawn and necessary future steps derived.

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* M.Sc., Institute of Space Systems, University of Stuttgart, PhD candidate, Pfaffenwaldring 29, 70569 Stuttgart, Germany.

† Prof. Dr.-Ing., Institute of Space Systems, University of Stuttgart, Institute Director, Pfaffenwaldring 29, 70569 Stuttgart, Germany.

‡ Priv.-Doz. Dr.-Ing., Institute of Space Systems, University of Stuttgart, Head Plasma Wind Tunnels and Electric Space Propulsion, Pfaffenwaldring 29, 70569 Stuttgart, Germany.

AAS 20-421

# EFFICIENT STARSHADE RETARGETING ARCHITECTURE USING CHEMICAL PROPULSION

**Thibault L. B. Flinois,[*] Carl R. Seubert,[†] Daniel P. Scharf,[†] and P. Douglas Lisman[‡]**

NASA is studying a possible starshade flying in formation with the Nancy Grace Roman Space Telescope (Roman). The starshade would perform weeks-long translational retargeting maneuvers between target stars. A retargeting architecture is introduced that is based on chemical propulsion and does not require ground tracking or interactions with the telescope during the retargeting cruise. Feasibility is demonstrated through a verified covariance analysis of the starshade-telescope relative position over several weeks using realistic sensor and actuator assumptions. Performance is sufficient for Roman to reacquire the starshade after retargeting and the architecture is shown to also be applicable to other mission concepts such as the Habitable Exoplanet Observatory (HabEx).

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[*] Payload/Instrument Pointing Control Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA.
[†] Spacecraft Guidance & Control Analysis Group, Ibid.
[‡] Instrument System Engineering Group, Ibid.

AAS 20-463

# CLOSED-LOOP LINEARIZED LAMBERT SOLUTION (LLS) FOR ON-BOARD FORMATION CONTROL AND TARGETING

**Taralicin Deka,[*] Hermann Kaptui Sipowa,[†] and Jay McMahon[‡]**

The Lambert's Problem is concerned with determining the transfer orbit between two given position vectors for a given time of flight under Keplerian dynamics. However, most existing solutions to this problem require an iterative root-finding method and are computationally expensive. To address this problem, the Linearized Lambert Solution (LLS) was developed in 2-Body dynamics to determine high accuracy solutions for neighboring transfers to a wide range of nominal transfers. In our work, we leverage the properties of the LLS and extend its application to externally perturbed environment. We apply this novel extension to Spacecraft Formation Flying (SFF) problems and demonstrate that a close-loop guidance algorithm designed around the LLS can be used in a perturbed environment to achieve high accuracy for a deputy spacecraft reconfiguration around a chief spacecraft. This resulting guidance algorithm allows a spacecraft formation to travel on a Lambert-like arc in the presence of perturbation such as, Drag, J2, Solar Radiation Pressure (SRP) with minimal targeting error. We formulate an optimization problem and demonstrate that our algorithm can be extended to satisfy mission constraints like maximum relative separation constraints with fuel-efficient transfers. We present ideas on how the same algorithm can be used when multiple spacecrafts are present in the formation. With some preliminary results we discuss our choice of Sampling based motion planning techniques for collision avoidance in the multiple spacecraft formation flying scenarios.

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[*] Graduate Research Assistant, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO 80303, USA. E-mail: Taralicin.Deka@colorado.edu.
[†] Graduate Research Assistant, Department of Aerospace Engineering Sciences.
E-mail: Hermann.KaptuiSipowa@colorado.edu.
[‡] Assistant Professor, Department of Aerospace Engineering Sciences. E-mail: jay.mcmahon@colorado.edu.

AAS 20-464

# DESIGN, IMPLEMENTATION, AND TESTING OF A TEARDROP TRAJECTORY RELATIVE ORBIT CONTROLLER

**Jason R. Crane,[*] Meghan Packard,[†] Michael Mercurio,[‡] Caleb Royer,[§] and Christopher W. T. Roscoe[**]**

Given Clohessy-Wiltshire-Hill assumptions, a ‘teardrop’ shaped relative motion trajectory can be derived for a deputy spacecraft relative to a chief spacecraft. In this work, an open loop teardrop trajectory controller was designed and implemented as a starting point for comparison with a subsequently developed closed loop version. Flight qualified software was leveraged to develop, implement, and test a practical teardrop closed loop controller that plans, executes, and repeats a teardrop relative trajectory above or below a target of interest while compensating for perturbations. The closed loop control solution involves a once-per-teardrop maintenance burn, which nulls accumulated perturbations across the vast majority of the teardrop period thus maintaining a stable, repeating teardrop trajectory. The work was then expanded to include investigation of a 3D teardrop open loop controller, which allows a spacecraft to remain in any given 3D region around the target of interest (radial, along-track and orbit-normal) using a once per teardrop period impulse control burn.

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[*] Aerospace Engineer, Space Domain Awareness, L3Harris, 10440 Little Patuxent Pkwy, Columbia, MD 21044, USA.
[†] Aerospace Engineer, Space Domain Awareness, L3Harris, 10440 Little Patuxent Pkwy, Columbia, MD 21044, USA.
[‡] Research Scientist, Space Domain Awareness, L3Harris, 10440 Little Patuxent Pkwy, Columbia, MD 21044, USA.
[§] Aerospace Engineer, Space Domain Awareness, L3Harris, 10440 Little Patuxent Pkwy, Columbia, MD 21044, USA.
[**] Research Scientist, Space Domain Awareness, L3Harris, 10440 Little Patuxent Pkwy, Columbia, MD 21044, USA.

AAS 20-468

# RAPID REACHABILITY ANALYSIS OF SINGLE IMPULSE SPACECRAFT RELATIVE MOTION MANEUVERS

**Costantinos Zagaris[*] and Joshuah A. Hess[†]**

Reachability analysis provides valuable insights into the behavior of dynamical systems but is often a computationally expensive process. This paper uses ellipsoidal techniques to formulate analytical approximations of reachable sets for spacecraft relative motion impulsive maneuvers. The analytical state transition matrix for the linearized relative equations of motion allows for an analytical expression of a terminal reachable set, a zero-input reachable set, and a zero-state reachable set. These sets are subject to a limited impulse magnitude and uncertainty in the initial relative state. Computation of these sets involves ellipsoidal operations, which are computationally efficient thus making onboard implementation possible. Onboard knowledge of these ellipsoidal reachable sets can be useful for autonomous guidance purposes as well as decision making regarding actions such as collision avoidance.

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[*] Assistant Professor, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.
[†] Assistant Professor, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

AAS 20-474

# ANALYSIS OF SRP-DISTURBED RELATIVE MOTION USING GEOMETRIC NONLINEAR CONTROL THEORY

**Hermann Kaptui Sipowa* and Jay W. McMahon†**

This work utilizes geometric nonlinear control tools to develop a nonlinear motion planner which allow to utilize Solar Radiation Pressure (SRP) to propelled spacecraft in formation. First, the controllability of the SRP-propelled Spacecraft Formation Flying (SFF) problem is investigated using nonlinear geometric control theory. The analysis utilizes Lie brackets to characterize reachable formation configuration using an SRP as the propelling mechanism. Then, a novel motion planning algorithm is proposed to determine feasible transfer trajectories between any two relative configurations. The planning algorithm is derived from the Riemannian manifold on which the SFF problem is defined, and it generates a minimum-distance curve while imposing constraints on both the states and the controls. Both theoretical portions of this work are applied to compute the transfer trajectory for a flat-plate deputy, around a cannon-ball chief spacecraft, in an SRP-disturbed environment.

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* Graduate Research Assistant, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO 80303, USA. E-mail: hermann.kaptuisipowa@colorado.edu.
† Assistant Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO 80303, USA. E-mail: jay.mcmahon@colorado.edu.

**AAS 20-492**

# AUTONOMOUS COOPERATIVE OPTIMAL CONTROL OF MULTI-AGENT SATELLITE FORMATIONS

**Devin E. Saunders,[*] Costantinos Zagaris,[†] Joshuah Hess,[‡] and Richard Cobb[§]**

This work demonstrates an optimal control for a multi-agent formation of satellites operating in close proximity to perform a dynamic formation maneuver. A candidate scenario is created in which a small team of four agents will alter its formation to match a desired configuration. Each agent has 3 degrees of freedom. Optimal control is proposed and solved which minimizes the control while staying in formation about a point. A modified Linear Quadratic Regulator problem allows the user to define arbitrary formation maneuvers with several tunable parameters to achieve desired pre- and post- maneuver conditions.

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[*] 2Lt., Masters Student, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson, OH 45431, USA.
[†] Maj., PhD, Assistant Professor of Aerospace Engineering, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson, OH 45431, USA.
[‡] Maj., PhD, Assistant Professor of Aerospace Engineering, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson, OH 45431, USA.
[§] PhD, Professor of Aerospace Engineering, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson, OH 45431, USA.

**AAS 20-493**

# APPLICATIONS AND LIMITATIONS OF ANGLES-ONLY RELATIVE NAVIGATION USING POLYNOMIAL SOLUTIONS

**Matthew Willis[*] and Simone D'Amico[†]**

Initial relative orbit determination from bearing angle measurements represents an enabling technology for autonomous space missions. This work addresses the range ambiguity issue by capturing nonlinear separation effects with a second-order Cartesian relative motion model for eccentric orbits. The system of polynomial constraint equations resulting from a series of line-of-sight measurements is solved numerically by homotopy continuation. Proof-of-concept is demonstrated for a variety of orbit scenarios, including the first application of angles-only relative navigation to hyperbolic flyby trajectories. Inherent limitations of the approach resulting from sensitivity to perturbing forces, measurement error, and uncertainty in the observer state are assessed.

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[*] PhD Candidate, Department of Mechanical Engineering, Stanford University, 496 Lomita Mall, Stanford, CA 94305, USA.
[†] Professor, Department of Aeronautics and Astronautics, Stanford University, 496 Lomita Mall, Stanford, CA 94305, USA.

**AAS 20-506**

# MODAL DECOMPOSITION OF SPACECRAFT RELATIVE MOTION IN QUASI-PERIODIC ORBITS

**Ethan R. Burnett[*] and Hanspeter Schaub[†]**

This paper develops new tools for close-proximity spacecraft relative motion guidance in slowly varying or quasi-periodic orbits in highly perturbed environments. The task of designing safe relative motion in this context is achieved using transformations of the linearized relative motion dynamics in differential orbit elements, generated from a high-fidelity model. Notably, the periodic part of the time-varying plant matrix is sampled over a quasi-period via Fourier transformations, and used to obtain modal decompositions in a transformed space for which the dynamics are linear time-invariant (LTI). As the spacecraft orbits evolve, the Fourier coefficients of the periodic component of the plant matrix change, the most robust relative motion modes change only slowly, and the effects of the nonperiodic part of the plant matrix are secondary. Thus, only small corrective maneuvers are needed for a spacecraft to continually follow sufficiently close to a desired modal motion.

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[*] Research Assistant, NDSEG Fellow, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80309, USA.

[†] Glenn L. Murphy Chair of Engineering, Smead Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, CO 80309-0431, USA. AAS Fellow, AIAA Fellow.

AAS 20-528

# RELATING COLLISION PROBABILITY AND MISS DISTANCE INDICATORS IN SPACECRAFT FORMATION COLLISION RISK ANALYSIS

**Ulises E. Núñez Garzón[*] and E. Glenn Lightsey[†]**

Active spacecraft formation flying collision avoidance schemes monitor collision risk through indicators such as miss distance and collision probability. This paper compares collision probability measures based on planar projections to their three-dimensional counterparts. In this analysis, it is found that the former overestimate the latter. Additionally, this work compares the consistency of risk assessments based on miss distance and collision probability. Certain statistics of relative position are well suited for collision risk assessments because their local minima and collision probability local maxima are anticorrelated, and vice versa. These results help connecting both types of indicators into a cohesive framework.

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[*] Graduate Research Assistant, Space Systems Design Lab, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, 620 Cherry St NW, Atlanta, GA 30332, USA.

[†] Professor, Space Systems Design Lab, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, 620 Cherry St NW, Atlanta, GA 30332, USA.

AAS 20-554

# HIGH VALUE ASSET PROTECTION THROUGH SWARM-FACILITATED STATE OBFUSCATION AND RESOURCE SHARING

Tristyn Jane Noone* and Norman G. Fitz-Coy†

The operating environment of Earth orbit is rife with threats posed by debris, bad actors, and uncooperative RSOs which may be highly unpredictable and pose a critical threat to existing high value assets. In this paper, we propose a networked formation of small satellites capable of detecting, classifying, and tracking such threats, and we address the significant initial challenge of determining the optimal state for each satellite required to maintain a stable formation over an extended period of time. By the conclusion, we will identify key areas for future research needed for this concept to succeed.

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* Research Assistant, Aerospace Engineering, University of Florida, 571 Gale Lemerand Drive, Gainesville, FL 32611, USA.

† Associate Professor, Aerospace Engineering, University of Florida, 571 Gale Lemerand Drive, Gainesville, FL 32611, USA.

AAS 20-560

# GUIDANCE, NAVIGATION, AND CONTROL FOR THE DWARF FORMATION-FLYING MISSION

Vincent Giralo,* Michelle Chernick,† and Simone D'Amico‡

The Demonstration with Nanosatellites of Autonomous Rendezvous and Formation-Flying (DWARF) mission consists of a pair of identical 3U CubeSats which will act as a space-borne testbed to further advance, rigorously validate, and embed new relative navigation and control technologies in order to meet the needs of future distributed space systems. This paper focuses on the design and implementation of the DWARF on-board Guidance, Navigation, and Control (GNC) system. The DWARF mission will demonstrate unprecedented real-time centimeter-level navigation accuracy on board and new safe, robust, and autonomous relative orbit control algorithms.

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* Doctoral Candidate, Stanford University, Department of Aeronautics and Astronautics, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, CA 94305-4035, USA.
† Doctoral Candidate, Stanford University, Department of Aeronautics and Astronautics, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, CA 94305-4035, USA.
‡ Assistant Professor, Stanford University, Department of Aeronautics and Astronautics, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, CA 94305-4035, USA.

AAS 20-601

# UNDERSTANDING OPTIMAL TWO-BURN RELATIVE TRAJECTORY TRANSFERS WITH MANEUVER ERRORS AND DISPERSION REQUIREMENTS

Nathan B. Stastny* and David K. Geller†

Two-burn transfers between relative spacecraft trajectories are easily defined by the Clohessy-Wiltshire equations. Though not commonly considered for optimal transfers, properly timed maneuvers can provide low fuel flight options for common mission scenarios. For this paper, the simplicity of the two-burn transfers is used to evaluate and provide broad understanding of the impact of maneuver errors on the trajectory dispersions and for identifying statistically optimal transfers. Results are also used to provide general insights into multiple transfer maneuvers common to on-orbit flight operations. This paper develops the closed-loop linear covariance equations for the two-burn scenario with lidar-based relative navigation and representative maneuver execution errors. The linear covariance equations are then used to evaluate an in-plane natural motion circumnavigation (NMC) resizing transfer. Nominal analysis of the NMC resizing reveals multiple global $\Delta V$ minima options for the transfer. The closed-loop linear covariance analysis is used to identify the $\Delta V$ usage dispersions (or the statistical estimate of total fuel consumption) given initial state uncertainty and maneuver execution errors. The results are compared to final state dispersion requirements to identify unique global minimum for the multiple scenarios.

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* Senior GNC Engineer, Space Dynamics Laboratory, North Logan, UT 84341, USA.
† Associate Professor, Mechanical and Aerospace Engineering, Utah State University, Logan, UT 84322, USA.

**AAS 20-605**

# DECENTRALIZED 6-DOF CONSENSUS CONTROL IN ORBITAL RELATIVE MOTION WITH HETEROGENEOUS COMMUNICATION DELAYS USING ROTATION MATRICES

**Mohammad Maadani*** **and Eric A. Butcher†**

6-DOF pose decentralized consensus control of multi-agent rigid body spacecraft systems in orbital relative motion under the presence of heterogeneous communication time delays is studied. The control objective is to stabilize the relative pose configurations with velocity synchronization of the spacecraft which share their states according to an undirected communication topology in the presence of gravitational forces and torques. For this purpose, the tangent bundle TSE(3) associated with Lie group SE(3) is used in which rotation matrices are utilized directly to parameterize attitude. An extension of Morse-Lyapunov-Krasovskii functional method is used to prove almost global asymptotic stability of the consensus subspace.

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* PhD Candidate, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, AZ 85721, USA. AIAA Member.

† Professor, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, AZ 85721, USA. AIAA Member.

AAS 20-606

# COLLISION-FREE FORMATION FLIGHT BASED ON HAMILTONIAN STRUCTURE-PRESERVING CONTROL

Yu Cheng,* Dong Qiao,† Yijun Lian,‡ and Changxuan Wen§

This paper studies the collision avoidance problem for the bounded formation obtained by the Hamiltonian structure-preserving control method, along the low-energy lunar halo transfer trajectory. Collision risk arises in close formations along the reference trajectory with given control gains. To avoid any possible collisions, an artificial potential approach is proposed to guarantee a minimum safety distance between the follower and the leader. The Hamiltonian structure of the collision-free controlled system can be preserved, and the sufficient condition to maintain the controlled stability is provided. Numerical results show that collision-free formation can be achieved by the proposed approach, and the control cost is less than 4 m/s for 1 km initial separation.

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* PostDoc, School of Aerospace Engineering, Beijing Institute of Technology. E-mail: chengyu8907@gmail.com.
† Professor, School of Aerospace Engineering, Beijing Institute of Technology. E-mail: qiaodong@bit.edu.cn.
‡ Associate Professor, School of Aeronautical and Astronautical Science, National University of Defense Technology. E-mail: lianyj academic@163.com.
§ Associate Professor, School of Aerospace Engineering, Beijing Institute of Technology.
E-mail: wenchangxuan@gmail.com.

AAS 20-620

# GEOMETRIC RELATIVE ORBITAL ELEMENT SET FOR MOTION NEAR A PERIODIC ORBIT WITH OSCILLATORY MODES

Ian Elliott[*] and Natasha Bosanac[†]

An important framework for relative trajectory design around periodic multi-body orbits is the description of the relative state between two spacecraft in a non-Keplerian environment. To characterize relative motion around a periodic orbit with oscillatory modes in the circular restricted three-body problem, a set of geometry-based relative elements are defined using first-order quasi-periodic motion expressed in a Hill frame. Mappings between the relative elements and relative Cartesian state elements are derived. The relative elements are used to straightforwardly design transfers for impulsive formation reconfiguration around periodic orbits with oscillatory mode in the Earth-Moon system.

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[*] Graduate Research Assistant, Colorado Center for Astrodynamics Research, Smead Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80303, USA.

[†] Assistant Professor, Colorado Center for Astrodynamics Research, Smead Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80303, USA.

# THREE SATELLITES FORMATION FLYING: DEPLOYMENT AND FORMATION ACQUISITION USING RELATIVE ORBITAL ELEMENTS

**Francesca Scala,[*] Gabriella Gaias,[†] Camilla Colombo,[‡] and Manuel Martin-Neira[§]**

This paper presents the analysis for the deployment and the acquisition procedures for a three-satellites formation flying, on a sun-synchronous orbit, as part of a study for a European Space Agency potential high resolution L-band radiometer mission for land and ocean applications. The methodologies for formation-flight establishment and reconfiguration maneuvers are presented, to enable the operational phase which foresees a continuous low-thrust control profile to keep the formation rigid and safe. The design is performed using relative orbital elements, including maximum delta-v limitation, safety condition requirements, and perturbation effects. The results, verified through high-fidelity propagation, apply to a wide range of Earth observation missions exploiting distributed systems.

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[*] Ph.D. Student, Department of Aerospace Science and Technology, Politecnico di Milano, 20156, Milano, Italy.
[†] Research Engineer, Department of Aerospace Science and Technology, Politecnico di Milano, 20156, Milano, Italy.
[‡] Associate Professor, Department of Aerospace Science and Technology, Politecnico di Milano, 20156, Milano, Italy.
[§] Technical Officer Engineer, European Space Agency, ESA-ESTEC, 2200 AG, Noordwijk, The Netherlands.

AAS 20-632

# FUEL-OPTIMAL PATH PLANNING FOR AN EARTH-ORBITING LINEAR SPACE INTERFEROMETER

**Hirotaka Kondo,* Sho Ishiwata,* Satoshi Ikari,† Taro Matsuo,‡ and Shinichi Nakasuka§**

Space interferometry by Earth-orbiting spacecraft has been considered as an important step to realize large-scale interferometric missions in the future. Because more perturbations on relative orbits exist in Earth orbits, formation control strategy needs to account for more complicated orbital dynamics rather than a simple model assumed by existing methods. In order to assure stable observation by an interferometer, periodic relative orbits are used for both continuous and point coverage of uv-plane. For point coverage of uv-plane, numerical optimization is introduced, and then the proposed method is validated numerical simulation.

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* Master's Degree Student, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyoku, Tokyo, 113-8656, Japan.
† Assistant Professor, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan.
‡ Associate Professor, Department of Physics, Graduate School of Science, Nagoya University, Furocho, Chikusa-ku, Nagoya, Aichi, 464-8602, Japan.
§ Professor, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan.

AAS 20-641

# SAFE TRAJECTORY DESIGN FOR CLOSE PROXIMITY OPERATIONS

**Gabriella Gaias[*] and Marco Lovera[†]**

This work addresses the design of safe relative trajectories to enable satellite close proximity operations for a variety of multi-satellite missions. With regard to active debris removal and on-orbit servicing applications, first the key aspects driving the different operational concepts are identified. Afterwards, these are translated into requirements for the trajectory design, carried out in the relative orbital elements framework. As a result, the paper provides guidelines and methodologies to compute relative trajectories applicable to different mission scenarios, considering the optimality in the location of the maneuvers and safety considerations.

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[*] Research Engineer, Department of Aerospace Science and Technology, Politecnico di Milano, 20156, Milano, Italy.
[†] Full Professor, Department of Aerospace Science and Technology, Politecnico di Milano, 20156, Milano, Italy.

AAS 20-657

# IMPACT OF ELECTROSTATIC PERTURBATIONS ON PROXIMITY OPERATIONS IN HIGH EARTH ORBITS

**Kieran Wilson[*] and Hanspeter Schaub[†]**

Orbital rendezvous is a highly challenging operation conducted in space, but is required for a range of missions. While low Earth orbit rendezvous has become routine with vehicles ferrying astronauts and cargo to the International Space Station, a range of missions propose to rendezvous in near-Geostationary orbit. This region is known to experience high levels of electrostatic charging, which can result in perturbing intercraft forces and torques during proximity operations. A range of proximity operations that model a servicing mission with an non-functional target are modeled to evaluate the impact of electrostatic perturbations, including rendezvous trajectories and static holds. Perturbing electrostatic torques are evaluated using the multi-sphere method and result in the target body rotating, requiring the servicer to maintain its relative position by translation. Electrostatic perturbations induced by potential magnitudes that have been observed at high earth orbits are found to be significant. Following a nominal rendezvous trajectory with 10 kV on each spacecraft results in the target rotating over 280° at up to 0.1°/s prior to docking, while a 5 hour hold at 10 meters separation under the same conditions can result in 100-fold increase in control effort over an unperturbed case, and can be even larger depending on the relative positions of the servicer and target.

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[*] Graduate Research Assistant, Ann and H.J. Smead Aerospace Engineering Sciences Department, University of Colorado Boulder 80301, USA.
[†] Glenn L. Murphy Endowed Chair, AIAA and AAS Fellow, Ann and H.J. Smead Aerospace Engineering Sciences Department, University of Colorado Boulder 80301, USA.

AAS 20-660

# THE FULL-BODY KEPLER'S PROBLEM IN A NON-INERTIAL REFERENCE FRAME. A DUAL LIE ALGEBRA APPROACH

**Daniel Condurache***

The present research is focused on developing new methods for recovering a solution to the full-body Kepler problem in a non-inertial reference frame. Using the dual Lie algebra approach and dual quaternions, a representation theorem is provided for the full-body initial value problem. Furthermore, the representation theorems for the rotation part and translation part of the full-body Keplerian motion in a non-inertial reference frame are obtained. Regarding the translation part, a closed-form coordinate-free solution is revealed based on generalized trigonometric function in space at constant curvature. They hold for all types of inertial trajectories (elliptic, parabolic, hyperbolic, rectilinear). The proof of concept is sustained by computational solutions.

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* Dept. of Theoretical Mechanics, Technical University of Iasi, D. Mangeron Street no.59, 700050, Iasi, Romania. Member AAS, Senior Member AIAA.

AAS 20-667

# VISUAL SERVOING USING PREDOMINANT SURFACE NORMALS FOR SPACECRAFT FINAL APPROACH

Wyatt J. Harris,[*] Richard Cobb,[†] and Costantinos Zagaris[‡]

A visual servo control law is proposed to maneuver a chaser spacecraft with respect to a non-cooperative unknown target resident space object during the final approach phase of rendezvous and proximity operations (RPO). The method exploits a novel variant of visual servo control that utilizes a stereo camera and the estimated predominant surface normal vector of a region of interest (ROI) on the target to calculate control commands. Unlike traditional methods of visual servo control, the proposed method decouples control of relative position and attitude. A translational controller seeks to drive the centroid of the target ROI to a desired position defined in the camera frame, while the attitude controller seeks to point the optical axis of the camera sensor in a direction aligned with the predominant surface normal vector of the target ROI. A method is proposed to estimate the predominant surface normal vector of the target ROI using a dense depth map provided by a stereo camera sensor on board the chaser spacecraft. Simulation results show that the method can control complex final approach maneuvers and precisely achieve a desired relative position and attitude with respect to the target ROI, even if the ROI contains significant nonplanar features. Notably, unlike other proposed methods for this type of RPO, this method does not require complex relative pose estimation algorithms or natural feature point tracking methods.

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[*] PhD Candidate, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

[†] Professor of Aeronautics and Astronautics, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

[‡] Assistant Professor of Aerospace Engineering, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, USA.

**AAS 20-670**

# ROTATIONAL CONTROL WITH PLUME IMPINGEMENT TO AID THE RIGID CAPTURE OF AN UNCOOPERATIVE FAILED SATELLITE

**Giacomo Borelli,[*] Gabriella Gaias,[†] and Camilla Colombo[‡]**

In the framework of Active Debris Removal (ADR) missions employing rigid capture mechanism, the rotational state of the target object greatly influences the feasibility, safety and cost of the capture operations. In this work, the impingement with thruster's plume gases is studied as a strategy to control the target tumbling motion and aid the final approach and robotic operations. The target objects considered in this study are small spacecraft in low Earth orbit, i.e. asset of large constellations, which may require in the future an ADR service solution to ensure the space environment sustainability. A simplified model of the thruster plume is used, and a guidance and control solution is proposed to drive the uncooperative target towards some useful rotational states, defined considering the target geometrical and inertia properties. Simulation results are presented, discussing the feasibility, cost and robustness of the introduced control strategies to increase the collaboration of the failed satellite to be serviced. An additional output is the provision of preliminary guidelines for the grapple fixture location to allow future servicing to an uncooperative failed space assets when a tumbling rate damping phase is required.

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[*] Research Fellow, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34, 20156 Milano – Italy.
[†] Senior Research Fellow, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34, 20156 Milano – Italy.
[‡] Associate Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34, 20156 Milano – Italy.

**AAS 20-697**

# GUARDIAN MAPS-BASED ADAPTIVE AND ROBUST CONTROL OF SPACECRAFT FORMATION FLYING

**Yazan Chihabi*** **and Steve Ulrich†**

In this paper, a single parameter guardian maps-based adaptive control system for spacecraft formation flying is developed. When compared with traditional vehicles, the dynamics of spacecraft features larger non-linearities, tighter coupling and stronger uncertainty. Specifically, as the eccentricity of an orbit increases, the non-linearities become even more apparent. The proposed approach addresses the problem of controlling a chaser spacecraft such that it tracks a desired relative trajectory with respect to the target spacecraft, regardless of disturbances. Making use of Guardian Maps theory, a standard proportional-derivative controller can be made adaptive such that the desired closed-loop stability of the system is guaranteed throughout the orbit. Simulation results for a projected circular formation example are provided to illustrate the increased performance and robustness of the proposed adaptive controller compared to a conventional non-adaptive linear quadratic regulator control law.

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* Ph.D. Student, Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON, Canada, K1S5B6.

† Associate Professor, Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON, Canada, K1S5B6.

AAS 20-707

# CLOUDSAT & CALIPSO A STUDY IN FORMATION FLYING

**Barbara Manganis Braun[*] and Clifford Graham[†]**

NASA's CloudSat mission was launched in 2006 and flew in formation with other earth-observing satellites in NASA's Afternoon Constellation (the "A-Train") for approximately 12 years. In February 2018, a series of reaction wheel anomalies forced CloudSat to exit the A-Train, however in October 2018, CloudSat established a new formation at a lower altitude with its previous formation-flying partner, the French CALIPSO satellite. In this new orbit, CloudSat – which normally experiences less drag than CALIPSO, and therefore must conduct orbit-lowering maneuvers to avoid falling too far behind – would occasionally appear to accelerate toward CALIPSO (as if it were experiencing more drag), necessitating an orbit raise to stay in formation. This was a novel situation, having never occurred before in 10+ years of formation-flying with CALIPSO within the A-Train. After investigation, a combination of circumstances that result in this behavior appears to have been identified. This paper will describe how low solar activity, combined with periods of very slightly higher eccentricity and slightly lower semi-major axis for CloudSat's orbit, result in an "inversion" of the normal relative acceleration profile between the two satellites. All three conditions must be present to experience the effect, which is subtle: CloudSat has larger variations in eccentricity and semi-major axis compared to CALIPSO. The paper will describe the effect, how it was uncovered, and how it has modified procedures for CloudSat maneuvers to minimize the effects of these new acceleration profiles.

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[*] Systems Director, The Aerospace Corporation, 2155 Louisiana Blvd NE., Suite 5000, Albuquerque, NM 87110, USA.
[†] Project Engineer, The Aerospace Corporation, 2155 Louisiana Blvd NE., Suite 5000, Albuquerque, NM 87110, USA.

AAS 20-708

# ON-BOARD RELATIVE GUIDANCE FOR SWARM MISSIONS NEAR COLLINEAR LIBRATION POINTS

**Donna Jennings[*] and Henry Pernicka[†]**

The potential use of small satellites (SmallSats) to comprise swarms and formations has gained interest in recent years due to the low SWaP attributes they offer. However, these same benefits also present challenges, including formation/maintenance of the relative positions and attitudes of the members of the swarm. Here a relative guidance method is developed for onboard use in close proximity formation flying at collinear libration points. The method utilizes a two-level differential corrector with the Circular Restricted Three-Body Problem. The focus is on developing an autonomous relative guidance solution maintaining formation flight that can be implemented onboard SmallSats within their SWaP limitations. A preliminary example of a swarm in the vicinity of the Earth-Moon L2 point is studied and presented. In addition, future work and analysis is proposed to expand the method making it applicable to a range of missions.

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[*] Ph.D. Student, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, 400 W 13th St, Rolla, MO 65409-0050, USA. E-mail: dmjwd5@mst.edu.
[†] Professor of Aerospace Engineering and Dean's Educator Scholar, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, 400 W 13th St, Rolla, MO 65409-0050, USA.
E-mail: pernicka@mst.edu.

AAS 20-730

# MULTIPLE-PURSUER/ONE-EVADER ORBITAL PURSUIT–EVASION GAME BASED ON REACHABLE SET METHOD

**Pang Bo,* Qiao Dong,† Cheng Yu,‡ and Wen Changxuan§**

This paper investigates the multiple-pursuers/one-evader orbital pursuit-evasion game between spacecraft. Different from the classic one-pursuer/one-evader case, multiple pursuers results in an extremely complex terminal condition so that the Nash equilibrium is hard to find. To overcome this difficulty, a method based on the reachable set is proposed, which can help to analyze the terminal state of the game intuitively, find the Nash equilibrium, simplify the model, and thus improve the convergence of the problem. Numerical simulations show that the solution has high accuracy and the method is insensitive to the initial state of the spacecrafts.

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* PhD Student, E-mail: pangxie1106@sina.com.
School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China;
Key Laboratory of Autonomous Navigation and Control for Deep Space Exploration, Ministry of Industry and Information Technology, Beijing 100081, China.
† Professor, E-mail: qiaodong@bit.edu.com.
School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China;
Key Laboratory of Autonomous Navigation and Control for Deep Space Exploration, Ministry of Industry and Information Technology, Beijing 100081, China.
‡ Post-doctor, E-mail: chengyu8907@gmail.com.
School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China;
Key Laboratory of Autonomous Navigation and Control for Deep Space Exploration, Ministry of Industry and Information Technology, Beijing 100081, China.
§ Associate Professor, E-mail: wenchangxuan@gmail.com. School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China;
Key Laboratory of Autonomous Navigation and Control for Deep Space Exploration, Ministry of Industry and Information Technology, Beijing 100081, China.

AAS 20-731

# APPLICATIONS OF PROSCIUTTO PLOTS TO SPACE MISSION DESIGN

Davide Conte* and David B. Spencer†

This paper is focused on presenting the applications of prosciutto plots for *proximity* operations implemented into the space mission design procedure. *Prosciutto* plots are graphical tools meant to be used by mission designers to quantify and assess preliminary proximity operation maneuvers similar to pork chop plots that are used for interplanetary astrodynamics. *Prosciutto* plots are specifically meant to be used for periodic orbits in the circular restricted three-body dynamics. In fact, these plots allow mission designers to consider proximity operation maneuvers for the planned operations for various potential departure and arrival windows, giving flexibility and risk management in case the nominal maneuvers are compromised. After the initial conditions that are to be used for proximity operation maneuvers are statistically determined, prosciutto plots can be created utilizing a semi–analytical model that solves the three-body problem for spacecraft in close proximity. Orbital transfers and subsequent proximity operation maneuvers presented in this paper involve lunar and Mars-Phobos Distant Retrograde Orbits (DROs). Here, Time-of-Flight, *TOF*, is an independent variable and can be seen as a design parameter subject to the constraints provided by the statistically computed initial conditions of the chaser vehicle with respect to the target vehicle. In this paper an end-to-end mission design is presented, including proximity operation maneuvers. This aims at broadening the utilization of the methodologies proposed in this paper to space mission designers working on pre–Phase A and Phase A of the mission design process.

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* Assistant Professor, Department of Aerospace Engineering, Embry–Riddle Aeronautical University, 3700 Willow Creek Rd, Prescott, AZ 86301, USA.
† Professor, Department of Aerospace Engineering, The Pennsylvania State University, 229 Hammond Building, University Park, PA 16802, USA.

AAS 20-736

# ROBUST DISTRIBUTED CONTROL FOR FORMATION FLYING ALONG HALO ORBIT

Xingyu Zhou,[*] Dong Qiao,[†] Yu Cheng,[‡] and Changxuan Wen[§]

This paper is devoted to the robust distributed control method for multiple spacecraft formation flying along Sun-Earth L2 halo orbit, in the presence of uncertain disturbances. A distributed controller is proposed using a nonlinear saturation function, based on mutual communication topology modeled by a direct/undirect graph. Global convergence is proved for the proposed controller. Numerical simulation considers a regular tetrahedral formation as a rigid-body, with switching topologies, communication time delays, external disturbances and parameter uncertainty considered. By the proposed control technique, robust formation keeping and formation reconfiguration is achieved, and the 'rigid' configuration is approximately maintained.

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[*] PhD Student, E-mail: zhouxingyu@bit.edu.com. School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China.

[†] Professor, E-mail: qiaodong@bit.edu.com. School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China;

[‡] Post-Doctor, E-mail: chengyu8907@gmail.com. School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China.

[§] Associate Professor, E-mail: wenchangxuan@gmail.com. School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China.

**AAS 20-739**

# DESIGN OF ROBUST PASSIVELY SAFE RELATIVE TRAJECTORIES FOR UNCOOPERATIVE DEBRIS IMAGING IN PREPARATION TO REMOVAL

**Stefano Silvestrini,* Jacopo Prinetto,† Giovanni Zanotti‡ and Michèle Lavagna§**

Among the critical steps forward the success of future Active Debris Removal are missions to enhance the target knowledge and validate proximity operations. The ESA e.Inspector project, currently in phase-A, aims at preparing a smallsat mission ready to fly and inspect the Debris. This paper discusses the current baseline, ensuring required passively safe trajectories while imaging the uncooperative object. The definition of relative trajectories is robust against unknown, or partially known, target attitude profiles. To ensure control authority the smallsat uses low thrust engines; to enhance the data yield navigation robustness, on board cameras operate on VIS and IR band.

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* PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Italy.
E-mail: stefano.silvestrini@polimi.it.
† PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Italy.
E-mail: jacopo.prinetto@polimi.it.
‡ PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Italy.
E-mail: giovanni.zanotti@polimi.it.
§ Full Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Italy.
E-mail: michelle.lavagna@polimi.it.

AAS 20-742

# POWER SERIES SOLUTION OF NONLINEAR SPACECRAFT RELATIVE MOTION IN ELLIPTICAL ORBIT

Ayansola D. Ogundele* and Olufemi A. Agboola†

As interest in the use and launching of spacecraft for communications, earth observation, scientific experiment, navigation, manned missions to the Moon and Mars intensifies there is need for the design of efficient and high fidelity relative motion dynamics. This will in turn reduce possibility of spacecraft collisions and increase return on investment. In this paper, a systematic procedure of power series method is employed in the formulation and construction of new fundamental solutions of spacecraft relative motion in elliptical orbit with quadratic nonlinear terms. Firstly, nonlinear relative motion equation of Deputy spacecraft with respect to the chief spacecraft in elliptical orbit with quadratic nonlinear terms is extracted from the original nonlinear equation. Then, the resulting equation with time varying coefficients is rewritten in a standard form suitable for the application of power series method. Afterward, using Cauchy product method for the discrete convolution of two power series of the quadratic nonlinear terms, recursive relations are established for the radial, along-track and cross-track equations of motion and solved successively to obtain new analytic solutions which can be used for spacecraft formation flying analysis and rendezvous purposes. The numerical simulations showed that the new power series solutions gave good representation of the nonlinear relative motion dynamics.

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* Chief Engineer, Engineering and Space Systems Department, National Space Research and Development Agency, Obasanjo Space Center, P. M. B. 437, Opposite Pyakassa Junction, Abuja, Nigeria.
E-mail: ayansoladaniel@gmail.com.
† Director, Engineering and Space Systems Department, National Space Research and Development Agency, Obasanjo Space Center, P. M. B. 437, Opposite Pyakassa Junction, Abuja, Nigeria.

AAS 20-745

# H.E.R.M.E.S.: A CUBESAT BASED CONSTELLATION FOR THE NEW GENERATION OF MULTI-MESSENGER ASTROPHYSICS

**Andrea Colagrossi,[*] Stefano Silvestrini,[†] Jacopo Prinetto[‡] and Michèle Lavagna[§]**

H.E.R.M.E.S., a mission to fly in 2022, is the first 6 high performance 3U CubeSats LEO constellation to collect multi-messenger astrophysics data devoted through a fractionated payload strategy.

The paper describes the Mission Analysis performed to achieve the highest possible sky coverage Sky throughout the mission duration, exploiting an innovative tool to optimize the coordinated pointing strategy of the distinct space elements, coupled with their natural relative orbital dynamics.

A wide coverage analysis and communication passages optimization is discussed aiming to minimize the latency between the astrophysical event detection and its ground communication.

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[*] Postdoctoral Research Fellow, Department of Aerospace Science and Technology, Politecnico di Milano, Italy. E-mail: andrea.colagrossi@polimi.it.

[†] PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Italy. E-mail: tefano.silvestrini@polimi.it.

[‡] PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Italy. E-mail: jacopo.prinetto@polimi.it.

[§] Full Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Italy. E-mail: michelle.lavagna@polimi.it.

**AAS 20-761**

# OPTIMAL TRAJECTORY CONTROL OF SPACECRAFT FORMATION FLYING IN ELLIPTICAL ORBIT

**Ayansola D. Ogundele* and Olufemi A. Agboola†**

Optimal control, the process of determining control law and state trajectories over a period of time, is a generalization and one of the applications of calculus of variations. The approach, which is dynamic in nature, is widely used in aerospace applications because of the performance criticality required. In this paper, a time-varying cubic approximation model, containing linear dynamics referred to as Tschauner-Hempel equation and cubic nonlinear terms, is developed from the nonlinear relative motion dynamics of deputy spacecraft with respect to the chief spacecraft in formation flying with chief in elliptical reference orbit. Two optimal controllers, Linear Quadratic Regulator (LQR) and State Dependent Riccati Equation (SDRE) with four different linear-like parameterized structures, are designed for the approximated nonlinear equation. The LQR controller is suited for the linear dynamics while the SDRE controller captures both the linear dynamics and the nonlinear terms. Through numerical simulations, comparison is made between the two controllers. The designs are useful for rendezvous, proximity and spacecraft formation flying missions.

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* Chief Engineer, Engineering and Space Systems Department, National Space Research and Development Agency, Obasanjo Space Center, P. M. B. 437, Opposite Pyakassa Junction, Abuja, Nigeria. Email:ayansoladaniel@gmail.com.
† Director, Engineering and Space Systems Department, National Space Research and Development Agency, Obasanjo Space Center, P. M. B. 437, Opposite Pyakassa Junction, Abuja, Nigeria.

**AAS 20-764**

# NON-TETRAHEDRAL FORMATIONS FOR CUSP SCIENCE COLLECTION DURING THE MMS EXTENDED MISSION

**Trevor Williams,[*] Eric Palmer,[†] and Neil Ottenstein[‡]**

The Magnetospheric Multiscale (MMS) mission will in the future encounter the polar magnetospheric cusps. This will enable new types of science that MMS has not yet been able to study, and for which the current tetrahedral formations are not ideally suited. One good configuration for cusp science is a logarithmic string, where the spacecraft are stretched out along the orbital path with one pair relatively close, the next moderately spaced, and the last widely spaced. There is also scientific interest in configurations involving a string plus one or more spacecraft offset laterally. This paper describes flight dynamics preparations for flying such formations.

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[*] Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. Phone: (443)545-4736. Email: Trevor.W.Williams@nasa.gov. Associate Fellow, AIAA.
[†] Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center.
[‡] Aerospace Engineer, a.i. solutions, Inc.

**AAS 20-765**

# DEVELOPMENT OF APPROXIMATE SOLUTION OF LF TRANSFORMATION OF SPACECRAFT RELATIVE MOTION WITH PERIODIC-COEFFICIENTS

**Ayansola D. Ogundele[*] and Olufemi A. Agboola[†]**

The Lyapunov-Floquet (L-F) theory, a powerful result of Floquet theory, is one of the main tools for the stability analysis and study of nonlinear periodic systems. In this paper, Lyapunov-Floquet and modal transformations of the nonlinear approximation model of spacecraft relative motion, containing periodic state dependent coefficients (SDC), are developed. The transformations, advantageously, retain the stability characteristics of the original nonlinear relative motion dynamics. To provide a form to which averaging method can be applied, the nonlinear approximated equation of motion is scaled using the chief's eccentricity. Through the application of L-F transformation, the linear part with periodic coefficients is reduced to time-invariant form and the transformed periodic nonlinear part has coefficients with true anomaly as the independent variable. The modal transformation reduced LF transformed equation into a form containing Jordan canonical form. Afterward, the averaging method is applied to the L-F transformed equation to describe the evolution of the motion in terms of the average values of the dynamical variables. Both the LF and modal transformed relative motion equations and the averaged equations, with chief in elliptical orbit, present forms that are useful and applicable for spacecraft guidance, navigation and control, formation flying, rendezvous and proximity operations.

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[*] Chief Engineer, Engineering and Space Systems Department, National Space Research and Development Agency, Obasanjo Space Center, P. M. B. 437, Opposite Pyakassa Junction, Abuja, Nigeria.
E-mail: ayansoladaniel@gmail.com.

[†] Director, Engineering and Space Systems Department, National Space Research and Development Agency, Obasanjo Space Center, P. M. B. 437, Opposite Pyakassa Junction, Abuja, Nigeria.

# TRAJECTORY DESIGN AND OPTIMIZATION

AAS 20-416

# HOMOTOPIC APPROACH OF FREE-FINAL-TIME CONTINUOUS-LOW-THRUST TRAJECTORY OPTIMIZATION

Jinsung Lee* and Jaemyung Ahn†

In this paper, an indirect homotopic optimization approach of generating free-final-time non-planar continuous low thrust orbit transfer and rendezvous trajectory is presented. Using homotopy along with transversality condition from resulting two-point boundary value problem (TPBVP), the majority of different test cases were successfully converged to a local optimal solution. It is found that users can design and optimize the continuous-low-thrust spacecraft trajectory with given spacecraft mass and thruster parameters by slowly altering the boundary conditions to the user's desired initial and final orbit.

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* Master's Candidate, Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology.
† Professor, Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology.

**AAS 20-435**

# OPTIMIZATION OF THE LUNAR ICECUBE TRAJECTORY USING STOCHASTIC GLOBAL SEARCH AND MULTI-POINT SHOOTING

**Jacob A. Englander***
**David C. Folta†**
**Sun H. Hur-Diaz‡**

Lunar IceCube is a 6U cubesat that will launch on NASA's Artemis 1 mission in 2021. Lunar IceCube will separate from Artemis 1 shortly after translunar injection (TLI) and travel to its science orbit about the moon using its Busek Ion Thruster 3 (BIT-3) propulsion system. This paper describes a technique to rapidly design Lunar IceCube trajectories using the monotonic basin hopping (MBH) stochastic global search algorithm, along with low- and high-fidelity multipoint shooting transcriptions. This technique allows the Lunar IceCube team to rapidly adapt to changing initial conditions, spacecraft properties, and operational constraints.

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* Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
† Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center.
‡ Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center.

AAS 20-436

# LOW-THRUST TRANSFER TO INTERPLANETARY TRAJECTORIES FROM LUNAR TRAJECTORIES WITH RIDESHARE

**Darcey R. Graham,[*] Jacob A. Englander,[†] Nicholas J. Rattenbury,[‡] and John E. Cater[§]**

Accessing interplanetary space is challenging when using low thrust systems. Injecting spacecraft onto interplanetary trajectories is difficult with small launch vehicles, but it is possible to instead transfer to an interplanetary trajectory from a lunar flyby. Such cases are useful, for example, in rideshares between lunar and interplanetary missions. This work examines the problem of rideshare for small satellites onto lunar flyby trajectories, with transfers to an interplanetary trajectory. Low thrust interplanetary trajectories are examined starting from a rideshare mission on a lunar trajectory using delivery systems based on a modified Rocket Lab USA Electron vehicle and Photon stage.

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[*] PhD Student, Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand.
[†] Aerospace Engineer, NASA Goddard Space Flight Center, Navigation and Mission Design Branch, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA. Member AAS.
[‡] Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand.
[§] Department of Engineering Science, University of Auckland, Private Bag 92019, Auckland, New Zealand.

**AAS 20-437**

# DISTANT-CIRCULAR SOLAR-SAIL ORBITS, A NEW CONCEPT FOR POLAR OBSERVATION OF THE EARTH AND MOON

**Fernando Gámez Losada[*] and Jeannette Heiligers[†]**

In this paper, a new family of solar-sail periodic orbits with adequate properties for polar observation of the Earth and Moon is developed under the simplified but non-autonomous dynamics of the Earth-Moon circular-restricted three-body problem. The novel orbits, coined distant-circular orbits, employ a simple Sun-facing steering law for the solar sail. A basic coverage analysis shows that one of the distant-circular orbits is capable of providing continuous coverage of both the Earth's and lunar North (or South) poles with just a single sailcraft for a minimum elevation of 14 deg and an average range of six Earth-Moon distances. Moreover, simple transfer trajectories between orbits of the family are found, so that the sailcraft can switch between observing the northern and southern latitudes during a sole mission. To assess the impact of higher-fidelity effects, the results are migrated via multiple-shooting differential correction to a higher-fidelity dynamical framework which considers, among others, the eccentricity of the Moon's orbit. Despite the higher-fidelity effects, the trajectories remain close to the distant-circular orbits, allowing them to maintain their coverage capabilities.

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[*] Graduate Student, Department of Astrodynamics and Space Missions, Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS, Delft, The Netherlands.
[†] Assistant Professor, Department of Astrodynamics and Space Missions, Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS, Delft, The Netherlands.

AAS 20-438

# LOW-THRUST TRAJECTORY OPTIMIZATION FOR MAXIMUM MISSED THRUST RECOVERY MARGIN

Chandrakanth Venigalla,* Jacob A. Englander,† and Daniel J. Scheeres‡

This paper introduces a new technique for directly optimizing the missed thrust recovery margin (MTM) of a low-thrust spacecraft trajectory. MTM is defined here as the amount of time a spacecraft may coast away from a nominal trajectory while still being able to reach a terminal manifold once thruster operations are resumed. The proposed "virtual swarm" optimization technique simultaneously optimizes the nominal spacecraft trajectory along with many recovery trajectories in order to maximize the MTM of the nominal trajectory at its weakest point. We develop the technique for a direct transfer and for a transfer that includes a gravity assist. Further, we show how to find the Pareto front of MTM, arrival mass, and arrival date to address the related multi-objective optimization problem.

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* Ph.D. Student, Department of Aerospace Engineering Sciences, University of Colorado Boulder, CO 80309, USA.
† Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
‡ A. Richard Seabass Chair Professor, Department of Aerospace Engineering Sciences, University of Colorado Boulder, CO 80309, USA.

**AAS 20-446**

# ECCENTRIC EXCURSIONS FROM PERIODIC ORBITS IN THE ELLIPTIC RESTRICTED THREE-BODY PROBLEM

**Kenta Oshima***

This paper explores the use of the instability peculiar to the planar elliptic restricted three-body problem. A proposed technique, called an eccentric excursion, gradually changes the eccentricity of unstable manifolds emanating from periodic orbits via multiple high-altitude flybys. As an application to the high-eccentricity, high-mass ratio, binary main-belt comet 288P system, a combination of a global search for planar symmetric periodic orbits and the use of the eccentric excursion finds a possible parking periodic orbit, from which landers are able to reach the surface of the primary or the secondary with the excited eccentricity.

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* Assistant Professor, Hiroshima Institute of Technology, Hiroshima, 731-5193, Japan.
Tel: +819071255894.
E-mail: k.oshima.nt@cc.it-hiroshima.ac.jp.

AAS 20-451

# DIRECT FLYOVER OF A TARGET OF INTEREST WITH CONSIDERATION OF $J_2$ PERTURBATIONS

**Aaron B. Hoskins***

The monitoring of an unexpected event (such as a natural disaster or nefarious activity by a hostile nation) may not be optimal with the groundtrack of a satellite. Small maneuvers can improve the groundtrack to facilitate the desired data collection. The problem investigated by this research is formulated as a two-stage stochastic program with the first-stage consisting of the selection of initial orbital parameters and the second-stage containing the maneuver sequence to monitor a latitude/longitude pair that is unknown at the launch of the satellite constellation. Because of the long-duration monitoring that is required, the perturbing $J_2$ force is included in the model to better represent the true dynamics and fuel usage that the constellation will encounter while observing the unexpected event.

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* Assistant Professor, Department of Mechanical and Industrial Engineering, California State University, Fresno, 2320 E. San Ramon Ave., MS/EE 94, Fresno, CA 93740-8030, USA.

AAS 20-452

# DESIGNING TRAJECTORIES RESILIENT TO MISSED THRUST EVENTS USING EXPECTED THRUST FRACTION

Ari Rubinsztejn,[*] Carrie Grace Sandel,[†] Rohan Sood,[‡] and Frank E. Laipert[§]

With the adoption of efficient low-thrust propulsion methods, the probability of a missed thrust event occurring has become a significant concern for short and long-duration missions. If the missed thrust events take place during a critical portion of the trajectory, the mission can be compromised. Therefore, it is essential to develop trajectories that are resilient to missed thrust events. This paper investigates the use of expected thrust fraction, which embeds the stochastic nature of missed thrust events into a deterministic optimal control problem. The performance of trajectories designed using expected thrust fraction is compared with traditionally designed trajectories to measure changes in resiliency to missed thrust events. In this investigation, trajectories designed using expected thrust fraction arrive with a median lateness half that of traditionally designed trajectories. Using expected thrust fraction can help astrodynamicists mitigate risks posed by the use of low-thrust propulsion.

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[*] Ph.D. Student, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL, 35487, USA. E-mail: arubinsztejn@crimson.ua.edu.
[†] Undergraduate Student, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL, 35487, USA. E-mail: cgsandel@crimson.ua.edu.
[‡] Assistant Professor, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL, 35487, USA. E-mail: rsood@eng.ua.edu.
[§] Mission Design Engineer, Flight Path Control Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA. E-mail: Frank.E.Laipert@jpl.nasa.gov.

# APPLYING TRAVELING SALESMAN PROBLEM TECHNIQUES TO OPTIMALLY VISIT EASILY RECOVERABLE OBJECTS FOR HARNESSING RESOURCES

**David Wu,[*] Kyle T. Alfriend,[†] and Manoranjan Majji[‡]**

Emerging interest in space exploration has increased the need for harnessing the resources of asteroids known as Easily Recoverable Objects (EROs). Accordingly, an optimal order of visitation was shown to be the minimum distance 3D path through the set of points defined by the orbital elements of the EROs. This optimal order is the solution to the modified 3D Traveling Salesman Problem (TSP). Then, the wait times and transfer times were analyzed and optimized by using waiting orbits, and by performing a visual inspection to exclude the more fuel-demanding EROs. The methods of determining the optimal order of visitation were exemplified.

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[*] Senior Undergraduate Student, Department of Aerospace Engineering, Texas A&M University, TAMU 3141, College Station, TX 77843-3141, USA. E-mail: pilotdavidwu@tamu.edu.
[†] TEES Eminent Professor of Aerospace Engineering, Department of Aerospace Engineering, Texas A&M University, TAMU 3141, College Station, TX 77843-3141, USA. E-mail: alfriend@tamu.edu.
[‡] Assistant Professor, Department of Aerospace Engineering, Texas A&M University, TAMU 3141, College Station, TX 77843-3141, USA. E-mail: mmajji@tamu.edu.

AAS 20-480

# DESIGN OF THE PHASING TRAJECTORY FROM A LOW LUNAR ORBIT TO NEAR RECTILINEAR HALO ORBIT

**Giordana Bucchioni[*] and Mario Innocenti[†]**

The paper presents three different approaches to the design of a phasing trajectory in a cis-lunar environment, where the third body perturbation is considered non-negligible. The working framework is the one proposed by the ESA's Heracles mission in which the passive target spacecraft -LOP-G- is orbiting on a Near Rectilinear Halo Orbit and the Lunar Ascent Element must reach that orbit from a Low Lunar Parking Orbit to start the rendezvous procedure. In this scenario the authors propose three different ways to design such phasing manoeuvre under the Circular Restricted Three Body Problem hypotheses: Lambert/Differential correction, Hohmann/Differential correction and Optimization. The three approaches are compared in terms of $\Delta V$ consumption, accuracy and time of flight. Finally, a selected solution is also validated under the Restricted Elliptic Three Body Problem Hypotheses.

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[*] PhD candidate, Department of Information Engineering, University of Pisa, Largo Lucio Lazzarino 2, 56122, Pisa (PI), Italy.
[†] Full Professor, Department of Information Engineering, University of Pisa, Largo Lucio Lazzarino 2, 56122, Pisa (PI), Italy.

AAS 20-484

# HOPPING WITH AN ADAPTIVE HOP PROBABILITY DISTRIBUTION

**A. C. Englander,[*] J. A. Englander,[†] and M. J. Carter[‡]**

Monotonic Basin Hopping (MBH) is a stochastic global search technique that may be used to design complex interplanetary trajectories. Previous research on MBH empirically demonstrated that a bi-polar Pareto distribution is an effective way to generate search "hops." However, no analytical foundation exists to explain this performance. In this work we provide the beginning of that analytical foundation and also introduce a new variant of MBH that uses an adaptive probability distribution to generate the hops. The technique is demonstrated on historical interplanetary trajectory design problems.

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[*] Department of Electrical and Computer Engineering, University of New Hampshire, Kingsbury Hall, Durham, NH 03824, USA. E-mail: ace@englander-associates.net.
[†] Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
[‡] Department of Electrical and Computer Engineering, University of New Hampshire, Kingsbury Hall W319, Durham, NH 03824, USA.

AAS 20-491

# IMPACT OF ANALYTIC DERIVATIVES ON OPTIMIZATION OF N-IMPULSE ORBIT TRANSFER

**Ahmed Ellithy,[*] Ossama Abdelkhalik,[†] and Jacob Englander[‡]**

Several formulations are possible for the optimization of N-impulse two-body orbit transfers. One formulation that assumes the first $N - 1$ impulses are design variables, and implements Lambert's algorithm in the final leg is here considered. This paper presents a derivation for the analytic expressions of the gradients needed to optimize this formulation. The impact of using these analytic expressions on the optimization computational cost is also presented. A linear system of equations is developed that approximates the Lambert's problem solution in a way that is suitable for computing the analytic gradients. The derivations of the analytic gradients, as well as numerical case studies for 2-impulse and 3-impulse orbit transfers, are presented. The numerical case studies highlights a significant reduction in the computational cost, measured in terms of the number of function calls.

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[*] PhD Student, Aerospace Engineering Department, 1200 Howe Hall, Iowa State University, Ames, IA 50011, USA. E-mail: ellithy@iastate.edu.

[†] Associate Professor, Aerospace Engineering Department, 1200 Howe Hall, Iowa State University, Ames, IA 50011, USA. E-mail: ossama@iastate.edu. Member AIAA.

[‡] NASA Technologist, NASA Goddard Space Flight Center, Greenbelt MD 20771, USA.

**AAS 20-495**

# STOCHASTIC PRIMER VECTOR FOR ROBUST IMPULSIVE TRAJECTORY DESIGN UNDER UNCERTAINTY

**Kenshiro Oguri* and Jay W. McMahon†**

Space trajectories are inherently subject to a considerable amount of uncertainties. Ideally, mission designers need to optimize trajectories while dealing with possible uncertainties. However, if naïvely formulated, trajectory design problems under state uncertainties would generally have an infinite number of variables to characterize the uncertain state distributions at each epoch. This paper presents an approach that aims to formulate the hard problem into a tractable, deterministic form. The bottleneck part of the problem, uncertainty quantification in the optimization routine, is greatly simplified by the choice of an orbital element coordinate to represent the uncertain orbital state. Some other technical aspects, namely an exact, tractable computation of planetary impact chance constraint, square-root formulation, and gradients of the unscented transform, are also developed to facilitate the convergence. The presented approach is partially demonstrated with a portion of Galileo-like planet tour trajectory.

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* Ph.D. candidate, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, UCB, Boulder, CO 80303, USA.

† Assistant Professor, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, UCB, Boulder, CO 80303, USA.

AAS 20-507

# DYNAMICAL BARRIER PREVENTING LOW-ENERGY BALLISTIC TRAJECTORIES FROM LANDING AT HIGH LATITUDES ON EUROPA

Luke Bury* and Jay McMahon†

The use of low-energy trajectories developed from three-body dynamics can help make missions to the moons of outer planets both feasible and safe. However, a previous study by the authors found that these low-energy trajectories are restricted from reaching high latitudes on the surface of secondary bodies by some sort of dynamical boundary. In this study, the high-latitude barrier is investigated at Europa. Numerical proofs are used to show the unreachable nature of high latitude locations, the phase spaces occupied on either side of the dynamical barrier are studied, and baseline values on impulsive $\Delta$Vs required to reach high-latitude locations from low-energy trajectories in the $L_2$ neck are determined.

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* PhD Student, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80303. E-mail: luke.bury@colorado.edu.

† Assistant Professor, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80303, USA. E-mail: jay.mcmahon@colorado.edu.

AAS 20-521

# DESIGN OF LOW THRUST TRAJECTORIES FROM LOW EARTH ORBIT TO DISTANT RETROGRADE ORBITS BY PARTICLE SWARM OPTIMIZATION

Sharad Sharan* and Robert G. Melton†

The endeavor of human interplanetary missions to Mars could greatly benefit from the employment of a spacecraft fuel depot stationed in a Distant Retrograde Orbit (DRO) around the Moon. In view of this, optimum low thrust trajectories from a low Earth orbit (LEO) to several lunar DROs are designed in this paper using Particle Swarm Optimization (PSO). Lunar DROs of different amplitudes are also generated in the circular restricted three body problem (CR3BP) using PSO. A low thrust Earth-escape spiral is designed using modified equinoctial elements in the Earth-centered inertial frame and later patched with the transfer arc designed using the CR3BP equations in the synodic frame. A fuel efficient trajectory is presented for each case, with each case targeting a different amplitude DRO. Several injection points on the DROs are also studied for their feasibility to allow a minimum-fuel transfer. The final-to-initial mass ratios for all cases and their optimal control policies for the thrust steering angles are studied quantitatively in this paper.

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* M.S., Department of Aerospace Engineering, The Pennsylvania State University, 229 Hammond Building, University Park, PA 16802, USA.

† Professor, Department of Aerospace Engineering, The Pennsylvania State University, 229 Hammond Building, University Park, PA 16802, USA. AAS Fellow, AIAA Associate Fellow.

**AAS 20-527**

# LOW-THRUST MULTIPLE GRAVITY ASSIST MISSIONS

**Ghanghoon Paik[*] and Robert G. Melton[†]**

The application of continuous low thrust to a gravity assist can result in extra gain of $\Delta v$ after the maneuver. In this paper, low thrust is applied to a gravity assist maneuver around Venus to evaluate possible benefits. Particle swarm optimization is applied to find the optimal sphere-of-influence entry location and the thrust direction and magnitude. Once the full trajectory is determined, the characteristics of both free and thrusted gravity assists are compared to evaluate the benefit of additional thrust over free gravity assist. Thrusted maneuvers show improvement in $\Delta v$ gain and closer approach to a planet.

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[*] PhD Candidate, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA.
[†] Professor, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. AAS Fellow, AIAA Associate Fellow.

AAS 20-531

# ITERATIVE PATCHED CONIC TECHNIQUE FOR LUNAR TRANSFER TRAJECTORIES

**Varshith Reddy*** **and R. V. Ramanan†**

An iterative patched conic technique is presented for lunar transfer trajectories. In the design process, apart from Earth and Moon, the perturbation due to the oblateness of Earth is also accounted for. The patch point at the sphere of influence of the Moon is iterated upon and an improved solution is obtained. An analytical tuning strategy is used to achieve the selenocentric velocity at the patch point on the sphere of influence of Moon. Numerical propagation results show that the analytical design thus generated is a good substitute for the numerical scheme to generate the transfer trajectory design. The proposed technique, unlike the conventional patched conic technique, captures all the four design options for a given departure epoch and flight duration and ensures arrival orbit inclination. Two sets of solutions were observed with small differences in the right ascension of ascending node and argument of perigee of departure transfer orbit characteristics. Differences of up to 3 degrees are noticed for both angles in each pair of solutions. The Iterative Patched Conic Method is suitable for design analysis since it gives quick and near-accurate solutions for all possible design options.

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* Undergraduate Student, Dept. of Aerospace Engineering, Indian Institute of Space Science and Technology, Trivandrum, Kerala, India – 695547.
† Adjunct Professor, Dept. of Aerospace Engineering, Indian Institute of Space Science and Technology, Trivandrum, Kerala, India – 695547.

AAS 20-532

# DESIGN OF A DEEP SPACE ORBIT TRANSFER VEHICLE (DS-OTV) ARCHITECTURE

Roger Gutierrez Ramon,* Yuying Liang,† and Yuichi Tsuda‡

Low-cost, recurring architectures for space access are gaining momentum recently. This study presents the design of a Deep Space Orbit Transfer Vehicle (DS-OTV) in the Earth's vicinity. Families of periodic and transfer orbits are computed and analyzed with the aid of stability-energy plots. Low-energy and impulsive transfer maneuvers are designed between the orbits by exploiting intersection of the stable/unstable manifolds. Resonant orbits are generated on the basis of maximizing rendezvous opportunities between the spacecraft and the creation of orbital chains that allow for a flexible architecture. Finally, an estimation of the feasibility of the mission is carried out.

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* PhD Student, Department of Space and Astronautical Science, The Graduate University for Advanced Studies, SOKENDAI, ISAS/JAXA, 252-5210 Kanagawa-ken, Sagamihara-shi, Chuo-ku, Yoshinodai 3-1-1.
† Post-doctoral Fellowship, Department of Solar System Science, ISAS/JAXA, 252-5210 Kanagawa-ken, Sagamihara-shi, Chuo-ku, Yoshinodai 3-1-1. E-mail: liang.yuying@ac.jaxa.jp.
‡ Professor, Department of Space and Astronautical Science, ISAS/JAXA, 252-5210 Kanagawa-ken, Sagamihara-shi, Chuo-ku, Yoshinodai 3-1-1.

**AAS 20-539**

# MULTI-LUNAR-FLYBY TRAJECTORIES USING COLLISION ORBITS

**Ferran Gonzalez-Franquesa[*] and Yasuhiro Kawakatsu[†]**

Small-scale spacecraft with limited propulsive capability that require high delta-v to achieve their targets may resort to low-energy transfers, such as flyby maneuvers. Trajectories that flyby the Moon multiple times can obtain mounting changes in the spacecraft's orbital energy. This work presents an approach for quickly computing multi-lunar-flybys with Moon-to-Moon collision orbits in the Sun–Earth–Moon four-body problem as building blocks. The combined solar and lunar gravitational effect in the vicinity of Earth allow the spacecraft to hop between collision orbits until it attains the necessary energy. These transfers have been positively assessed; they present a promising solution space that spans a wide range of energy levels within practical times of flight.

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[*] PhD Student, Department of Space and Astronautical Science, SOKENDAI, The Graduate University for Advanced Studies, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-210 Japan.
[†] Professor, Department of Space Flight Systems, Japanese Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-210 Japan.

**AAS 20-550**

# MULTI-OBJECTIVE OPTIMIZATION OF COVARIANCE AND ENERGY FOR ASTEROID TRANSFERS

**Erica L. Jenson[*] and Daniel J. Scheeres[†]**

This paper presents a multi-objective optimization approach to minimize both error covariance and energy. Linear covariance dynamics and a continuous thrust model with control-dependent noise are implemented. Two formulations are considered: 1) a combined cost function with weighted covariance and energy terms and 2) a minimum covariance cost function with an energy constraint. In general, Formulation 1 is easier to implement, but Formulation 2 is a more rigorous approach to multi-objective optimization. However, a Theorem is presented to prove that the necessary conditions for optimality are equivalent in both formulations for the specific case herein. The former is used to locate Pareto-optimal trajectories with indirect single shooting methods. To provide an explicit example of this approach, it is applied to orbital maneuvers about an asteroid. Terminator orbit transfers, phasing maneuvers, and "proactive station-keeping" maneuvers are optimized, and the results indicate that significant uncertainty reduction is possible with small penalties in energy cost.

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[*] PhD Student, Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80303, USA.
[†] Distinguished Professor, Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80303, USA.

**AAS 20-561**

# NETWORK ANALYSIS OF TISSERAND GRAPHS FOR AUTOMATED GRAVITY-ASSIST PATHFINDING

**James W. Moore* and James M. Longuski†**

We present a network analysis of the Tisserand graph that automates the identification of pure (ballistic) gravity-assist paths given a launch planet and a destination planet. The network approach extends the utility of the Tisserand graph to tours with many gravity assists. Such tours are impractical to assess with the existing graphical techniques. The network uses information found in the Tisserand graph and the related two-body problem assumptions to search for attractive paths. We deploy a search method that generates an exhaustive list of potential paths (subject to search-limiting criteria) and use a shortest-path search (Dijkstra's algorithm) to identify fast paths. Candidate paths to Neptune evaluated in a patched-conic propagator compare favorably with the network analysis predictions.

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* Doctoral Candidate, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave. West Lafayette, IN 47907-2045, USA. Currently at Intuitive Machines, 3700 Bay Area Blvd, Houston, TX 77058, USA. AIAA Member.

† Professor, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave. West Lafayette, IN 47907-2045, USA. AAS Member, AIAA Associate Fellow.

AAS 20-562

# ECLIPSE AVOIDANCE IN DYNAMICAL STRUCTURES NEARBY NRHOS IN A HIGHER-FIDELITY MODEL

**Emily M. Zimovan-Spreen,* Kathleen C. Howell,† and Diane C. Davis‡**

A dynamical understanding of orbits in the Earth-Moon neighborhood, particularly in the vicinity of the NRHOs, is relevant to future long-duration missions in this region. Power, thermal, and line of sight constraints dictate allowable eclipsing conditions for spacecraft. In response, characteristics of significant dynamical structures nearby the NRHOs, including eclipse-avoidance properties, are verified in a higher-fidelity ephemeris model. An eclipse avoidance strategy, based on resonance with the lunar synodic period and the incorporation of a path constraint within a targeting scheme, is developed and verified. As a result, long-duration, eclipse-free trajectory solutions in a higher-fidelity model are constructed.

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* Ph.D. Candidate, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, IN 47907-2045, USA.

† Hsu Lo Distinguished Professor of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, IN 47907-2045, USA.

‡ Principal Systems Engineer, a.i. solutions, Inc., 2224 Bay Area Blvd., Houston, TX 77058, USA.

**AAS 20-563**

# TRAJECTORY OPTIMIZATION FOR OSIRIS-REX EARTH RETURN

**Noble Hatten, Jacob A. Englander, Donald H. Ellison[*]**
**Ryo Nakamura[†]**
**Brian Sutter[‡]**
**Kenneth E. Williams, Jeremy M. Knittel, James McAdams, Daniel Wibben, Peter Antreasian[§]**
**Kenneth Getzandanner[**]**
**Michael C. Moreau[††]**
**Dante S. Lauretta[‡‡]**

The Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) mission is currently operating in proximity to the near-Earth asteroid (NEA) Bennu. OSIRIS-REx is scheduled to perform a Touch and Go (TAG) sample acquisition in the fall of 2020 and then return the sample to Earth. This paper details the design and optimization of the Earth-return trajectory. Daily departure trajectories for several months surrounding the baseline departure date of March 3, 2021 are presented, along with the results of trade studies examining departure dates through September 2022. The capabilities of the trajectory optimization engine used in this work—NASA Goddard Space Flight Center's (GSFC) Evolutionary Mission Trajectory Generator (EMTG)—are also described, with an emphasis on newer features that enable EMTG to optimize the OSIRIS-REx Earth-return trajectory.

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[*] Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
[†] Japan Aerospace Exploration Agency; Visiting Researcher, Navigation and Mission Design Branch, NASA Goddard Spaceflight Center, Greenbelt, MD 20771, USA.
[‡] Lockheed Martin Space, Littleton, CO 80125, USA.
[§] Space Navigation and Flight Dynamics Practice, KinetX Aerospace, Simi Valley, CA 93065, USA.
[**] Flight Dynamics Lead, OSIRIS-REx, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
[††] Deputy Project Manager, OSIRIS-REx, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA.
[‡‡] Principle Investigator, OSIRIS-REx, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

# LOW-THRUST TRANSFERS TO CANDIDATE NEAR-RECTILINEAR HALO ORBITS FACILITATED BY INVARIANT MANIFOLDS

**Sandeep K. Singh,[*] Brian D. Anderson,[†] Ehsan Taheri[‡] and John L. Junkins[§]**

Near-Rectilinear Halo Orbits (NRHOs) are deemed to be favorable candidates for establishing a near-future crewed space station in the cis-lunar space. Although the 9:2 resonant southern $L_2$ NRHO has been earmarked as the working orbit for the Lunar Gateway Mission, a plethora of other neighboring resonant NRHOs are also viable options. The invariant manifolds of these periodic orbits provide natural pathways to a state in the vicinity of fixed points on the NRHOs. These manifolds can be leveraged while designing optimal low-thrust trajectories for both 'NRHO-bound' and 'Earth-bound' missions. In this work, the effects of the ephemeris model (JPLs DE436) on three NRHO manifolds derived based on the Circular Restricted Three Body (CR3BP) assumptions are characterized and presented. The three neighboring NRHOs are then investigated in the domain of the aforementioned mission categories for piece-wise minimum-time and minimum-fuel, low-thrust transfers facilitated by invariant manifolds of the NRHOs. The minimum-time and minimum-fuel trajectory optimization problems are formulated using the indirect formalism of optimal control and solved using a single-shooting solution scheme. The relative merits of the stable manifolds are studied with regard to minimizing either mission time of flight or minimization of fuel consumption, for a set of representative low-thrust family of transfers.

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[*] PhD Student, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. AAS Member.
[†] Current employment is Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
[‡] Assistant Professor, Department of Aerospace Engineering, Auburn University, Auburn, Alabama 36849, USA. AIAA Member.
[§] Distinguished Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. Honorary Fellow AIAA.

# MISSION DESIGN FOR A SOLAR SYSTEM FAST ESCAPE TO INTERSTELLAR MEDIUM AND SOLAR-GRAVITY LENS FOCUS*

**Reza R. Karimi,† Michael Preudhomme,‡ Jonathan Sauder,§ Juergen Mueller,** Dean Cheikh,†† Nitin Arora,‡‡ and Leon Alkalai§§**

Mission concepts were designed for a fast escape to Interstellar Medium (ISM) and solar system lens focus using two main different mission architectures and three different technologies. In the first mission architecture, a low launch C3 using an SLS launch family vehicles can deliver a large launch mass that would enable a big burn at solar perihelion (Oberth maneuver) resulting in a big DV for escaping the solar system. After the solar perihelion burn, generated by a Solar Thermal Propulsion (STP) technology, low thrust, enabled by a Nuclear Electric Propulsion (NEP) system, to further accelerate the spacecraft. Same architecture was tried using a Solid Rocket Motor (SRM) instead of STP at solar perihelion. The second mission architecture does not use the dive maneuver back to the solar perihelion and instead takes advantage of a very high launch C3 with a much smaller probe and performing a Jupiter powered flyby (using SRM technology at Jupiter) followed by NEP technology (low thrust). Results showed both mission architectures yielded comparable promising results, but since the STP technology is still immature as of 2020, a combination of SRM and NEP would be ideal for time being. For shorter distances in deep space like KBO's, relying on more SRM than NEP would be more efficient, whereas for very far deep in space like solar gravity lens focus (SGLF) and beyond, NEP's effect is dominant. To reach Interstellar medium, a combination of both SRM and NEP is the most efficient. A hypothetical enhanced STP system resulted in a very high escape velocity.

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† Mission Design Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
‡ Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
§ Mechatronics Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
** Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
†† Technologist, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
‡‡ Blue Origin, Kent, WA 98032, USA.
§§ Capture Lead and Engineering Fellow, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

# MULTI-LEG OCCULTATION AVOIDANCE MANEUVERS FOR THE LUNAR RECONNAISSANCE ORBITER

Mark Karpenko,* Michael K. Barker,† and Julie K. Halverson‡

Lunar Reconnaissance Orbiter (LRO) has been in orbit around the Moon since 2009. Recently, a gyroless attitude control mode that uses LRO's star trackers for deriving angular rate has been implemented to reduce reliance on an aging inertial measurement unit. In the new gyroless mode, star tracker occultations are not allowed during attitude maneuvers. Consequently, many scientific observations can no longer be performed. In this paper, we develop and solve a continuous-time trajectory optimization problem to design multi-leg occultation avoidance maneuvers comprising simple Euler rotations about each of the spacecraft body-fixed axes. The appropriate number of slew legs and the associated sequence of rotation axes are determined automatically through the use of a new geometric constraint that naturally enforces LRO's taxicab motion profile. Application to Lunar Orbiter Laser Altimeter (LOLA), one of LRO's seven scientific instruments, is described. To date, the new approach has been used to implement more than 100 occultation avoidance maneuvers for the LOLA instrument.

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* Research Associate Professor and corresponding author, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, USA. E-mail: mkarpenk@nps.edu.
† Research AST, Planetary Studies, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.
‡ Lead Systems Engineer, Space Sciences Mission Operations, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

**AAS 20-577**

# AN ASSESSMENT OF VIRTUAL REALITY TECHNOLOGY FOR ASTRODYNAMICS APPLICATIONS

**Davide Guzzetti,[*] Dhathri H. Somavarapu,[†] and Grant Turner[‡]**

Recent portable and affordable virtual reality (VR) devices may be a tipping point for the diffusion of immersive working environments. Our work focuses on an early assessment of modern VR technology for astrodynamics applications. The assessment is constructed by a review of VR-related works that are external to the typical astrodynamics community to facilitate cross-pollination of ideas. Next, the Johnson-Lindenstrauss lemma, together with a set of simplifying assumptions, is employed to analytically estimate the time-to-discovery within a dataset that is projected to lower dimensions. Finally, two astrodynamics applications are presented to demonstrate solutions that are primarily enabled by VR technology.

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[*] Assistant professor, Department of Aerospace Engineering, Auburn University, 211 Davis Hall, Auburn, AL 36849, USA.

[†] Graduate student, Department of Aerospace Engineering, Auburn University, 211 Davis Hall, Auburn, AL 36849, USA.

[‡] Undergraduate student, Department of Aerospace Engineering, Auburn University, 211 Davis Hall, Auburn, AL 36849, USA.

**AAS 20-579**

# AN ENERGY-INFORMED ADAPTIVE ALGORITHM FOR LOW-THRUST SPACECRAFT CISLUNAR TRAJECTORY DESIGN

**Bonnie Prado Pino[*] and Kathleen C. Howell[†]**

A near-term goal for the expansion of activities in the Earth-Moon neighborhood is the capability to maintain a facility near the Moon that serves as a staging node for excursions to other cislunar destinations. Support for low-thrust vehicles in this dynamically sensitive region include functional requirements that depend upon the scientific mission constraints and on the limitations introduced by the physical capabilities of the spacecraft1. This investigation offers an adaptive strategy for generating locally optimal solutions for low-thrust spacecraft in the lunar vicinity, by exploiting the energy parametrization of multi-body families of orbits. Results are validated in a higher-fidelity ephemeris model and are demonstrated for a variety of transfers with a wide range of thrust acceleration levels. The methodology proves successful for achieving large orbital plane changes evolving entirely within the lunar vicinity, as well as for generating suitable initial guesses for long spiral transfers approaching low lunar orbits.

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[*] PhD Candidate, Astrodynamics and Space Applications, School of Aeronautics and Astronautics, College of Engineering, Purdue University, West Lafayette, IN 47906, USA. E-mail: bpradopi@purdue.edu.

[†] Hsu Lo Distinguished Professor, School of Aeronautics and Astronautics, College of Engineering, Purdue University, West Lafayette, IN 47906, USA. E-mail: howell@purdue.edu.

AAS 20-582

# RAPID LOCAL TRAJECTORY OPTIMIZATION USING HIGHER-ORDER STATE TRANSITION TENSORS AND DIFFERENTIAL DYNAMIC PROGRAMMING

Spencer Boone* and Jay McMahon†

This paper presents an algorithm for rapid local trajectory optimization around a reference using the reference trajectory's higher-order state transition tensors (STTs) to approximate the local dynamics. Differential dynamic programming (DDP) is used within the STT-approximated dynamics to construct an analytical optimization scheme. The algorithm is applied to a complex low-thrust transfer in the Earth-Moon circular restricted three-body problem. Results show that the STT/DDP algorithm yields similar results to a numerical DDP algorithm when targeting new trajectories in the vicinity of the reference, but at a fraction of the computational cost. In addition, the method can accommodate any number of perturbations in the dynamics, and can incorporate many stage or penalty constraints that would be used in a standard DDP algorithm. The method could be promising for on-board applications with limited computational resources, or any situation where rapid continuous-thrust trajectory optimization is required.

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* Ph.D. Student, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80303, USA.

† Assistant Professor, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80303 80303, USA.

AAS 20-590

# LOGICAL END-POINT CONSTRAINTS IN CONTINUOUS-TIME OPTIMAL CONTROL

**Elliott L. VonWeller,[*] Mark Karpenko,[†] and Brian M. Wade[‡]**

In continuous-time optimal control problems, constraints must be satisfied as logical conjunctions. In many practical space missions, however, the end-point functions may contain disjunctions. In this paper, we present an approach for handling end-point function disjunctions as part of a single continuous-time trajectory optimization problem. This approach uses continuous representations of discrete logic operators as part of the problem formulation in order to model a disjunction. We analyze and illustrate the application of the new concept for a canonical double integrator model as a proxy for practical space flight applications.

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[*] MS Student, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, USA.
[†] Research Associate Professor and corresponding author, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, USA. E-mail: mkarpenk@nps.edu.
[‡] Director, The Research and Analysis Center - Monterey, Monterey, CA 93943, USA.

**AAS 20-593**

# TRAJECTORY DESIGN IN THE VICINITY OF 65803 DIDYMOS BASED ON THE CENTER MANIFOLD THEORY

**Naoki Hiraiwa,[*] Mai Bando,[†] and Shinji Hokamoto[‡]**

This paper considers the dynamical environment of 65803 Didymos and applies the center manifold approximation method to compute quasi-periodic orbits. Its dynamical environment is known to be complex due to the unique shapes of the primaries and the nonexistence of symmetric properties which is useful to obtain Lyapunov or halo orbits. The center manifold method is successfully applied and extended in Didymos. This method is beneficial because it does not require the initial guess nor bifurcation process and has a lower computational cost. Multiple shooting is introduced into the center manifold method to calculate trajectories with the longer propagation time.

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[*] Master Student, Department of Aeronautics and Astronautics, Kyushu University, 819-0395, Japan.
[†] Associate Professor, Department of Aeronautics and Astronautics, Kyushu University, 819-0395, Japan.
[‡] Professor, Department of Aeronautics and Astronautics, Kyushu University, 819-0395, Japan.

AAS 20-596

# EVALUATION OF TRANSFER COSTS IN THE EARTH-MOON SYSTEM USING THE THEORY OF FUNCTIONAL CONNECTIONS

**Allan K. de Almeida Junior,[*] Hunter Johnston,[†] Carl Leake,[‡] and Daniele Mortari[§]**

Fuel consumption and time of flight are crucial information for mission design. In this paper, adopting a two-impulse maneuver, we analyze the fuel consumption through evaluations of the equivalent $\Delta V$ for several transfers in the Earth-Moon system as function of time of flight and other parameters, like the points of application of the thrusts. Transfer costs from a LEO to the Lagrangian point $L_1$ are analyzed as functions of the departure position and the time of flight. Transfers from a near-Earth orbit to a near-Moon orbit are also analyzed. The influence of perturbations due to the gravitational attraction of the Sun is also investigated. These problems involve specific constraints, i.e. the initial and final positions are given, but the initial and final velocities are unknown. These are boundary value problems that are here efficiently solved using the Theory of Functional Connections. This yields to the construction of a 3-body porkchop, where the $\Delta V$ costs can be obtained in terms of the boundary values.

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[*] Postdoctoral Associate, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
E-mail: fenixcinza@tamu.edu.
[†] PhD Candidate, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
E-mail: hunterjohnston@tamu.edu.
[‡] PhD student, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
E-mail: leakec@tamu.edu.
[§] Professor, Aerospace Engineering, Texas A&M University, College Station, TX 77843, USA.
E-mail: mortari@tamu.edu. IEEE and AAS Fellow, AIAA Associate Fellow, and IAA Corresponding Member.

AAS 20-597

# AN INDIRECT LÈVY FLIGHT BASED APPROACH TO SOLVE OPTIMAL CONTROL PROBLEMS

**Thomas Palazzo*, and Puneet Singla†**

This paper provides a procedure for numerically solving optimization problems via indirect methods. To consistently generate good initial guess solutions, metaheuristic algorithms, that is, heuristic optimization algorithms with a natural metaphor, are used. These algorithms excel at arriving at close-to-optimal solutions to problems in the absence of *a priori* knowledge. The metaheuristic algorithms particle swarm optimization and the firefly algorithm are conventionally used for this purpose. This work exploits optimal foraging theory to modify the conventional firefly algorithm to incorporate the Lèvy flight foraging hypothesis. While most of the heuristic approaches rely on brownian motion based random search, the proposed algorithm utilizes the Lèvy distribution, a fat-tailed exponential probability distribution. These metaheurstics are used to bypass the difficulty of indirect methods by obtaining a good guess of the optimal solution which can then be used to initialize a two-point boundary value problem solver. To show the efficacy of this approach, three optimal control problems of varying difficulty are presented with the metaheuristic/indirect method approach successfully deriving the optimal solution in each case.

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* Graduate Student, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: trp31@psu.edu.

† Professor, Department of Aerospace Engineering, Pennsylvania State University, University Park, PA 16802, USA. E-mail: psingla@psu.edu. AIAA Associate Fellow, AAS Fellow.

AAS 20-602

# ESCAPE, PLASMA AND ACCELERATION DYNAMICS EXPLORERS (ESCAPADE) MISSION DESIGN

Jeffrey S. Parker,[*] Nathan Parrish,[†] Timothy Sullivan,[†]
Robert Lillis,[‡] Shannon Curry,[§] and David Curtis[**]

The Escape, Plasma and Acceleration Dynamics Explorers (ESCAPADE) mission will provide a comprehensive picture of how solar wind energy flows through Mars' unique hybrid magnetosphere to drive ion and sputtering escape. This paper provides a new examination into ESCAPADE's mission design, surveying each phase of the transfer from launch through the end of the primary science mission at Mars. The two ESCAPADE spacecraft launch as secondaries with Psyche and proceed thereafter to use solar electric propulsion, a Mars gravity assist, and aerobraking to achieve the mission. ESCAPADE's science includes two campaigns: the first involves both spacecraft being in the same orbit in a string-of-pearls configuration; the second involves both spacecraft traversing very different plasma regions about Mars.

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[*] Chief Technology Officer, Advanced Space, 2100 Central Ave, #102, Boulder CO 80301, USA.
[†] Astrodynamicist, Advanced Space, 2100 Central Ave, #102, Boulder CO 80301, USA.
[‡] Associate Research Physicist, UC Berkeley Space Sciences Laboratory, 7 Gauss Way, Berkeley, CA 94720, USA.
[§] Research Scientist, UC Berkeley Space Sciences Laboratory, 7 Gauss Way, Berkeley, CA 94720, USA.
[**] System Engineer, UC Berkeley Space Sciences Laboratory, 7 Gauss Way, Berkeley, CA 94720, USA.

# COMMUNICATION-AWARE ORBIT DESIGN FOR SMALL SPACECRAFT SWARMS AROUND SMALL BODIES

**Federico Rossi,[*] Saptarshi Bandyopadhyay,[*] Mark Mote,[†] Jean-Pierre de la Croix,[*] and Amir Rahmani[*]**

Exploration of small Solar System bodies has traditionally been performed by single monolithic spacecraft carrying a number of science instruments. However, science instruments typically cannot be operated simultaneously due to the instrument requirements including optimal viewing angle, surface illumination, altitude and ground resolution, power, and data constraints. This observation has motivated interest in multi-spacecraft architectures where a swarm of small spacecraft, each carrying a single science instrument, studies a small body after being deployed by a carrier spacecraft, which then collects data from the swarm and relays it to Earth. Such architectures hold promise to yield significant improvements in mission efficiency, increases in data quality, and reduced mission duration. A key difficulty in the design of such missions is the selection of orbits for the small spacecraft, which must satisfy not only instrument requirements, but also strict inter-spacecraft communication and on-board storage constraints. To address this, in this paper, we present a novel computationally-efficient optimization algorithm for communication-aware design of the orbits of a small-spacecraft swarm orbiting a small body. The proposed approach captures constraints including instrument requirements, inter-spacecraft communication bandwidths, and on-board memory usage, and it can accommodate highly irregular gravity field models and surface geometries. We propose an efficient algorithm for optimization of instrument observations and inter-spacecraft communications; we then leverage the differentiable nature of the proposed algorithm to accelerate a gradient-based global search algorithm. Numerical simulations of a six-spacecraft swarm studying 433 Eros show that the proposed approach successfully identifies high-quality orbits, and significantly outperforms communication-agnostic optimization techniques, resulting in a 10% increase in scientific returns and a 30% increase in the quality of the collected data.

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[*] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.
[†] Georgia Institute of Technology, 301 Ferst St., Atlanta, GA 30332, USA.

**AAS 20-607**

# IMPROVED TWO-IMPULSE TRANSFER TO HALO ORBITS IN EARTH-MOON ELLIPTIC RESTRICTED THREE BODY PROBLEM FRAMEWORK USING DIFFERENTIAL EVOLUTION

**Rithwik. N* and R. V. Ramanan†**

A new technique to design transfer trajectory of a space vehicle in an Earth parking orbit to multi-revolution (MR) halo orbits around Lagrangian points in the Earth-Moon system under the Elliptic Restricted Three Body Problem framework is presented. In the proposed technique, the whole transfer trajectory is treated as a single segment and achieved using two maneuvers, unlike the conventional manifolds approach which has two segments and three maneuvers. The first maneuver injects the space vehicle directly into the single segment transfer trajectory and the space vehicle reaches the MR halo orbit. The second maneuver inserts the space vehicle into the MR halo orbit. The bridge maneuver that transfers the space vehicle from transfer trajectory to the manifolds of the Earth-Moon system is avoided in the proposed technique. The location of insertion into the halo orbit and the components of the insertion velocity are treated as unknowns and obtained using differential evolution, an evolutionary optimization technique. The velocity impulses and flight durations obtained by the proposed technique are far lesser than those reported in the literature. The proposed technique can be used as an analysis tool to comprehend in-depth knowledge about various mission scenarios.

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* Research Scholar, Department of Aerospace Engineering, Indian Institute of Space Science and Technology, Kerala 695547, India.
† Adjunct Professor, Department of Aerospace Engineering, Indian Institute of Space Science and Technology, Kerala 695547, India.

AAS 20-615

# ANALYSIS OF 3GM CALLISTO GRAVITY EXPERIMENT OF THE JUICE MISSION

**Mauro Di Benedetto,[*] Paolo Cappuccio,[†] Serena Molli,[‡] Lorenzo Federici,[§] and Alessandro Zavoli[**]**

The ESA's JUICE mission will provide a thorough investigation of the Jupiter system and the Galilean moons during its nominal tour, comprising flybys of Europa and Callisto, and an orbital phase about Ganymede at the end of the mission. The 3GM experiment will exploit accurate Doppler and range measurements to determine the moons' orbits and gravity fields (both static and tidal) and infer their interior structure. This paper presents the attainable accuracies of the Callisto geodesy experiment and addresses the effect of different flybys mean anomaly distribution and geometry on the estimation of the tidal Love number k2.

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[*] 3GM Experiment Manager, PhD, Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza, Università di Roma, via Eudossiana 18, 00184, Rome, Italy.
[†] PhD Student of Aeronautical and Space Engineering, Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza, Università di Roma, via Eudossiana 18, 00184, Rome, Italy.
[‡] Graduate Student of Aeronautical and Space Engineering, Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza, Università di Roma, via Eudossiana 18, 00184, Rome, Italy.
[§] PhD Student of Aeronautical and Space Engineering, Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza, Università di Roma, via Eudossiana 18, 00184, Rome, Italy.
[**] Researcher, PhD, Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza, Università di Roma, via Eudossiana 18, 00184, Rome, Italy.

AAS 20-618

# CHANCE-CONSTRAINED COVARIANCE CONTROL FOR LOW-THRUST MINIMUM-FUEL TRAJECTORY OPTIMIZATION

Jack Ridderhof,[*] Joshua Pilipovsky,[†] and Panagiotis Tsiotras[‡]

The propellant mass required for a space mission can be greatly reduced by using low-thrust propulsion. Designing low-thrust minimum-fuel trajectories that are robust to disturbances, however, is a challenging optimal control problem. In this paper, we model the spacecraft dynamics as a stochastic system and then solve for both the optimal nominal trajectory and a corresponding feedback law, subject to probabilistic constraints on the thrust commands and on the target state mean and covariance. The optimal control is found by successively linearizing the dynamics and solving for the updated controls as a convex program. The proposed method is demonstrated for a low-thrust interplanetary trajectory from Earth to Mars.

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[*] Graduate Student, Georgia Institute of Technology, School of Aerospace Engineering.
[†] Graduate Student, Georgia Institute of Technology, School of Aerospace Engineering.
[‡] David and Andrew Lewis Chair and Professor, School of Aerospace Engineering, and Institute for Robotics and Intelligent Machines, Georgia Institute of Technology, Atlanta, GA, 30332, USA.

**AAS 20-624**

# MISSION DESIGN FOR THE 2020 MERCURY LANDER DECADAL SURVEY


**Jackson L. Shannon,[*] Justin A. Atchison,[†] Benjamin F. Villac,[†] Gabe Rogers,[‡] and Martin T. Ozimek[†]**



This paper presents the mission design for a Mercury Lander concept in support of the 2020 Planetary Science Decadal Survey. We evaluated both chemical and solar electric propulsion trajectory options for the interplanetary and orbital phases. Like previous missions, our solution uses a series of Venus and Mercury gravity assists to reduce the total delta-V needed to capture at Mercury. Solar electric propulsion offers significant propellant savings for the interplanetary phases, but results in unreasonably long flight times during the orbital lowering phase. Based on these trades, we selected a trajectory that uses a NEXT-C electric propulsion system with a baseline power of 9 kW to orbit match with Mercury. Upon arrival at Mercury, the electric propulsion stage is jettisoned, and a chemical system performs orbit insertion and lowering to the final orbit. Descent and landing are performed using a solid rocket motor and liquid propulsion system, respectively. The arrival is phased so that the lander can operate in local nighttime for up to 13 weeks, with direct-to-Earth communication availability for up to 7 weeks.



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[*] Ph.D. Student, Department of Aerospace Engineering, University of Maryland-College Park, College Park, Maryland 20740, USA.

[†] Mission Design Engineer, Astrodynamics and Controls Group, Space Exploration Sector, Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, USA.

[‡] Assistant Group Supervisor, Astrodynamics and Controls Group, Space Exploration Sector, Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, USA.

AAS 20-630

# TRAJECTORY OPTIMIZATION FOR ASTEROID CAPTURE INTO NEAR-EARTH ORBITS

**Jay Iuliano[*] and David A. Spencer[†]**

In this paper, capturing Near-Earth Asteroids (NEAs) into Near-Earth orbits is investigated. A general optimization strategy is employed whereby a genetic algorithm is used to seed a sequential quadratic programming (SQP) method for the first step, and then nearby solutions seed further SQP runs. A large number of solutions are produced for several asteroids with varying levels of thrust. Solutions were found over a range of epochs and times of flight as opposed to many traditional methods of optimizing point solutions. This methodology proved effective, finding low-thrust capture solutions within 10% of the required $\Delta V$ for analytically estimated transfers.

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[*] Ph.D. Candidate, Aeronautical and Astronautical Engineering, Purdue University, 701 W Stadium Ave, West Lafayette, IN 47907, USA.
[†] Associate Professor, Aeronautical and Astronautical Engineering, Purdue University, 701 W Stadium Ave, West Lafayette, IN 47907, USA.

**AAS 20-640**

# FORWARD PROPAGATING RICCATI EQUATION CONTROL OF SPACECRAFT ON EARTH-MOON L1 HALO ORBIT MISSION

**Alex Thompson[*] and Ilya Kolmanovsky[†]**

In support of crewed lunar missions, a permanent crewed outpost stationed in orbit around the L1 Earth-Moon Lagrange point would allow for reduced-cost access to the lunar surface and beyond. As Halo orbits are typically unstable, control is necessary to maintain the spacecraft on such an orbit. This paper considers the use of a Forward-Propagating Riccati Equation (FPRE)-based control to maintain the spacecraft on Halo orbit trajectories and to facilitate spacecraft transfer to and from such Halo orbits. While its formulation is similar to the traditional finite horizon LQR control, FPRE-based control integrates a modified Riccati differential equation forward in time rather than backward in time. Hence FPRE-based control can be applied over an arbitrary/infinite time horizon and does not require a priori knowledge of the linearized model of the spacecraft dynamics. Simulation results for FPRE-based control in the setting of the Circular Restricted Three Body Problem (CR3BP) are reported to illustrate the approach. It is shown that FPRE-based control can successfully stabilize the spacecraft motion on a Halo orbit and facilitate spacecraft transfer to and from this Halo orbit. Methods to reduce fuel consumption are considered and full mission profile is simulated from Earth parking orbit to the selected Halo orbit and back while exploiting FPRE-based control and stable and unstable manifold trajectories for the transfer.

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[*] MSE Student, Aerospace Engineering, University of Michigan, 3585 Greenbrier Blvd, Ann Arbor, MI 48105, USA.
[†] Professor, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, MI 48109, USA.
The second author acknowledges the support of the National Science Foundation Award Number CMMI 1562209.

AAS 20-644

# HELIOCENTRIC ACCESS FROM CISLUNAR SPACE WITHIN THE CONTEXT OF THE BICIRCULAR RESTRICTED FOUR-BODY PROBLEM

**Kenza Boudad,[*] Kathleen Howell[†] and Diane Davis[‡]**

In the next decades, multiple missions are proposed or planned to originate in the vicinity of the Moon and be delivered to heliocentric space, such as servicing missions to the Nancy Roman or the James Webb Space Telescopes, as well as departures from Gateway to other interplanetary destinations. The Earth-Moon-Sun transit dynamics are complex, primarily influenced by the Earth and the Moon in cislunar space; the gravitational influence of the Sun becomes significant after departure from the Earth-Moon vicinity. The current investigation leverages an Earth-Moon-Sun-spacecraft four-body model, the Bicircular Restricted Four-Body Problem, including dynamical structures in this regime such as periodic orbits and manifolds to design low-energy transfers from the cislunar space to the heliocentric orbits near the Sun-Earth $L_2$ portal.

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[*] Ph.D. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: kboudad@purdue.edu.
[†] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA. E-mail: howell@purdue.edu.
[‡] Principal Systems Engineer, a.i. solutions, Inc., 2224 Bay Area Blvd, Houston TX 77058, USA. E-mail: diane.davis@ai-solutions.com.

# LOW-THRUST MULTIPLE ASTEROID MISSIONS WITH RETURN TO EARTH USING MACHINE LEARNING

Giulia Viavattene* and Matteo Ceriotti†

Sample-return missions to near-Earth asteroids (NEAs) are invaluable for the scientific community to learn more about the initial stages of the solar system formation and life evolution. Thanks to its high specific impulse, a low-thrust propulsion technology is capable of performing multiple asteroid rendezvouses (to collect samples) and eventually returning to Earth. To identify the best asteroid sequences with return to Earth, this work proposes to employ machine learning techniques and, specifically, artificial neural networks (ANNs), to quickly estimate the cost of each transfer between asteroids. The ANN is integrated within a sequence search algorithm based on a tree search, which identifies the asteroid sequences and selects the best ones in terms of propellant mass required and interest value. This algorithm can design the sequences so that specific asteroids of interest, for which a sample return would be more valuable, can be targeted. A pseudospectral optimal control solver is then used to find the optimal trajectory and control history. The performance of the proposed methodology is assessed by analyzing three distinctive NEA sequences ending with return to Earth and rendezvous. A near-term low-thrust propulsion enables to rendezvous five asteroids, and ideally return samples to Earth in about ten years from launch. It is demonstrated that visiting more interesting asteroids from the scientific point of view increases the appeal of the sequence at the cost of a greater propellant mass required.

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* James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom.
E-mail: g.viavattene.1@research.gla.ac.uk.
† James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom.

AAS 20-653

# PRELIMINARY TRAJECTORY DESIGN FOR NASA'S SOLAR CRUISER: A TECHNOLOGY DEMONSTRATION MISSION

**James B. Pezent,[*] Rohan Sood,[†] Andrew Heaton,[‡] Kyle Miller,[§] and Les Johnson[**]**

This work outlines preliminary trajectory design for NASA's proposed sail-based Solar Cruiser spacecraft, which is a finalist to be a secondary payload launched with the Interstellar Mapping and Acceleration Probe (IMAP) in October 2024. Trajectory optimization is carried out to ensure that Solar Cruiser can successfully reach a halo orbit about a Sun-Earth sub-$L_1$ Lagrange point in under one year using only solar sail propulsion. Trade studies are performed to identify optimal trajectories subject to restrictions on sail-incidence angles and deployment times, and off nominal initial-conditions are examined to determine the feasibility of the baseline mission profile. Results, thus far, show that Solar Cruiser can be incorporated as a secondary payload on IMAP while satisfying tight operational restrictions. However, additional work must be done to mitigate risks from large launch vehicle injection errors.

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[*] PhD Student, Astrodynamics and Space Research Laboratory, The University of Alabama, 245 7th Ave, Tuscaloosa, AL 35401, USA. E-mail: jbpezent@crimson.ua.edu.
[†] Assistant Professor, Astrodynamics and Space Research Laboratory, The University of Alabama, 245 7th Ave, Tuscaloosa, AL, USA 35401, USA. E-mail: rsood@eng.ua.edu.
[‡] Senior Aerospace Engineer, EV/42, NASA Marshall Space Flight Center, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA. E-mail: andrew.f.heaton@nasa.gov.
[§] Aerospace Engineer, Guidance Navigation and Control Systems, NASA Marshall Space Flight Center, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA. E-mail: kyle.miller@nasa.gov.
[**] Solar Cruiser PI, Science Technology Office, NASA Marshall Space Flight Center, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA. E-mail: les.johnson@nasa.gov.

**AAS 20-656**

# MULTIPLE IMPULSE CISLUNAR TRANSFER VIA MULTI-FIDELITY APPROACH USING GPU-BASED SUPER PARALLELIZATION

**Satoshi Ueda[*] and Hideaki Ogawa[†]**

This paper presents a global trajectory optimization framework via a multi-fidelity approach that makes combined use of a graphics processing unit (GPU) for a low-fidelity initial solution search and a central processing unit (CPU) for high-fidelity optimization to determine solutions that satisfy constraints including Lawden's conditions in light of primer vector theory. The present study aims to identify optimum solutions robustly and flexibly by introducing multiple impulses that can further reduce the total velocity increments compared with two-impulse transfer. The proposed framework is examined with a mission scenario considering cislunar transfer from a near-rectilinear halo orbit (NRHO) to a low lunar orbit (LLO).

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[*] Associate Senior Researcher, Research and Development Directorate, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.
[†] Associate Professor, Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan.

AAS 20-658

# IMPROVING THE EVOLUTIONARY OPTIMIZATION OF INTERPLANETARY LOW-THRUST TRAJECTORIES USING A NEURAL NETWORK SURROGATE MODEL

**Leon Stubbig*** **and Kevin Cowan†**

Building on recent advances in the fields of low-thrust trajectory optimization based on shaping methods, Artificial Neural Networks, and surrogate models in Evolutionary Algorithms, an investigation into a novel optimization routine is conducted. A flexible Python tool to evaluate linked trajectories in a two-body model based on hodographic shaping is implemented and used to develop a novel evolutionary optimization approach where a Genetic Algorithm is assisted in finding new candidate solutions by an online surrogate. The algorithm and different surrogate designs are experimentally investigated on two example problems based on the Dawn trajectory and the GTOC2 problem. Employing the surrogate yields new candidate solutions that improve the population's fitness especially when the surrogate is used to approximate the shaping computation. Additionally, the use of a surrogate pretrained on a general data set of low-thrust transfers is tested and found to considerably improve the initial quality of the model, meaning that more good candidate solutions are found early on, accelerating the algorithm's convergence.

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* MSc Graduate, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.
E-mail: leon.stubbig@gmail.com. The manuscript for this paper was part of the author's MSc thesis.
† Education Fellow + Lecturer, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.
E-mail: k.j.cowan@tudelft.nl.

AAS 20-663

# GLOBAL OPTIMIZATION OF LOW-THRUST INTERPLANETARY TRAJECTORIES USING A MACHINE LEARNING SURROGATE

Pablo Gómez Pérez,* Yuxin Liu,† and Kevin Cowan‡

In this work, we propose a new method to approximate the cost function of Low-Thrust, Multiple-Gravity-Assist interplanetary trajectories using a Machine Learning surrogate. We identified the computation time required to obtain training data as the main limitation when using Machine Learning methods for this purpose so we present a strategy to build the surrogate with limited training data. We build an Online-Sequential Extreme Learning Machine Multi-Agent System (OS-ELM-MAS) surrogate due to its theoretical good performance when the training data is limited. In addition, we define a method to include the surrogate during the optimization process that can be used with any gradient-free algorithm, and study the effect of several surrogate parameters on the optimization results. Finally, several interplanetary trajectories are optimized with and without the surrogate. Employing the surrogate results in up to 12% lower fuel cost values after a fixed optimization time. The parameters that control the interaction have to be carefully selected to achieve this improvement, and we show that the optimal value of these parameters can be narrowed down based on the characteristics of the transfers.

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* M.Sc. Student, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.
E-mail: pablogope@gmail.com.
† Ph.D. Candidate, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.
E-mail: yuxin.liu@tudelft.nl.
‡ Education Fellow + Lecturer, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.
E-mail: k.j.cowan@tudelft.nl.

**AAS 20-669**

# TRAJECTORY OPTIMIZATION FOR DISTRIBUTED SPACE TELESCOPES

**Kyle Rankin,[*] Hyeongjun Park,[†] Neerav Shah,[‡] John Krizmanic,[§] Steven Stochaj,[**] and Asal Naseri[††]**

A distributed space telescope utilizes various components that are placed on multiple spacecraft to form a much larger effective telescope. The use of distributed space telescopes shows significant promise to substantially improve the performance of space-based telescopes compared to utilizing only a single spacecraft. By aligning an optics spacecraft and a detector spacecraft, a focal length within the range from tens of meters to a few kilometers or even longer can be achieved. One of the main challenges for these distributed space telescope missions is to align the optics spacecraft and the detector spacecraft precisely, especially to achieve fine imaging of astronomical sources. The detector spacecraft must maneuver to hold the alignment whenever the optics spacecraft position and attitude changes. This frequent maneuvering for adjusting the position and attitude of the detector spacecraft exhausts resources and therefore limits the mission lifetime of the distributed space telescope. The work depicted here presents a method for developing a propellant optimal trajectory to maneuver the distributed components of a telescope between different pointing directions, utilizing a non-traditional path-based cost function.

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[*] Graduate Student, Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces. NM 88003, USA.
[†] Assistant Professor, Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces. NM 88003, USA.
[‡] Deputy Project Manager, Project Formulation and Development Office, Goddard Spaceflight Center, Greenbelt. MD 20771, USA.
[§] Senior Scientist, University of Maryland Baltimore County, Center for Research and Exploration in Space Science, NASA Goddard Spaceflight Center, 8800 Greenbelt Road, Greenbelt. MD, 20771, USA.
[**] Professor, Electrical Engineering, New Mexico State University, Las Cruces. NM 88003, USA.
[††] Branch Head, Satellite Technologies, Space Dynamics Laboratory, Logan. UT 84341, USA.

**AAS 20-671**

# MULTIPLE GRAVITY-ASSIST LOW-THRUST TRAJECTORY DESIGN USING FINITE FOURIER SERIES

**Nicholas P. Nurre*  and Ehsan Taheri†**

In this paper, we propose a framework for generating low-thrust trajectories with multiple gravity-assist maneuvers using a finite Fourier series shape-based (FFS-SB) method. The FFS-SB method is capable of handling thrust and state constraints and can produce three-dimensional approximate fuel- and time-optimal trajectories. These features make the FFSSB method a promising candidate to be used as an inner-level solver within a dual-level hybrid optimization algorithm. Application of the proposed framework is demonstrated through solving a low-thrust trajectory from the Earth to asteroid 16 Psyche with one gravity assist with Mars. The results demonstrate the utility of the proposed tool in generating a pool of low-thrust multiple gravity-assist trajectories in a rapid manner while respecting constraints such as "forced" coast arcs, minimum distance from Sun, and maximum thrust magnitude.

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* Undergraduate Student, Auburn University, Auburn, AL 36849, USA.
† Assistant Professor, Department of Aerospace Engineering, Auburn University, Auburn, AL 36849, USA. AIAA Member.

**AAS 20-686**

# BROAD TRAJECTORY SEARCHES USING MONTE CARLO TREE SEARCH WITH THE INCLUSION OF ΔVEGA TRAJECTORIES

**Burton A. Yale,[*†] Rohan D. Patel,[*‡] Jehosafat J. Cabrera,[*§] and Navid Nakhjiri[* **]**

Multiple flybys of the inner planets and the application of $V_\infty$ leveraging are essential trajectory design techniques to reduce the required launch energy for interplanetary missions. These trajectories are often difficult to formulate and require extensive computational resources. However, this problem can be classified as a combinatorial task and can be solved by the Monte Carlo Tree Search (MCTS) method. In this paper, an MCTS algorithm is developed and tested. The tree search is able to incorporate $V_\infty$ leveraging of Earth ($\Delta V$ EGA), which will allow the algorithm to find an additional set of feasible sequences. Several cases are optimized and the tree search's performance and accuracy is discussed. This algorithm will allow for the inner-planetary flyby search planning for outer planet missions.

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[*] Aerospace Engineering, Cal Poly Pomona, 3801 W Temple Ave., Pomona, California 91786, USA.
[†] Undergraduate Student, E-mail: bayale@cpp.edu.
[‡] Undergraduate Student, E-mail: rohanpatel@cpp.edu.
[§] Undergraduate Student, E-mail: jehosafatc@cpp.edu.
[**] Assistant Professor, E-mail: nnakhjiri@cpp.edu.

AAS 20-693

# LOW-ENERGY TRAJECTORIES FROM GEOSYNCHRONOUS TRANSFER ORBITS TO LUNAR LIBRATION ORBITS

Alex Pascarella,* Ron Noomen,† and Roby Wilson‡

The ability to reduce the cost of space missions beyond Earth orbit by leveraging innovative concepts is of great interest in the field of spaceflight. In this paper, the trajectory design for a mission from an inclined geosynchronous transfer orbit (GTO) to an Earth-Moon L2 Halo orbit is presented. The mission scenario for this investigation involves the use of a small satellite launched in a rideshare configuration and the use of a low-energy transfer to reach the target orbit. As a consequence of choosing a rideshare launch, the mission scenario entails critical uncertainties on the time of launch and injection parameters of the spacecraft, which could complicate the insertion into a low-energy transfer. Thus, the goal of the project is to develop a robust design methodology to deal with the launch uncertainties and assess launch readiness at any time of the year.

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* Master Student, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, the Netherlands.

† Assistant professor, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, the Netherlands.

‡ Technical group supervisor, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, 91109 CA, USA.

**AAS 20-695**

# GEOMETRICAL TOOLS FOR THE SYSTEMATIC DESIGN OF LOW-ENERGY TRANSFERS IN THE EARTH-MOON-SUN SYSTEM

**Anastasia Tselousova,* Maksim Shirobokov,† and Sergey Trofimov‡**

Weak stability boundary (WSB) trajectories are Sun-perturbed low-energy trajectories connecting a near-Earth orbit and a lunar orbit. Among their benefits are the increased mass delivered to a working orbit and larger launch windows. However, the flight is much longer than for traditional high-energy lunar transfers. Since the discovery of WSB trajectories several decades ago, they have been being designed numerically, by a single or multiple shooting procedure. The major challenge is in choosing a good initial guess for that procedure: a WSB trajectory consists of legs with alternating fast/slow dynamics and is extremely sensitive. The paper presents several geometrical tools that enable the systematic design of a high-quality initial guess in the framework of the planar bicircular four-body problem. The constraints on the launch energy $C_3$ and the selenocentric distance of the lunar orbit insertion point are satisfied by construction. The initial-guess planar WSB trajectory is then fed to the standard multiple shooting procedure in order to get a three-dimensional trajectory with the trans-lunar injection from a specific parking orbit adapted to the realistic ephemeris model. The technique developed is ideologically similar to the patched conic approximation for high-energy trajectories: the region of prevalence concept introduced by R. Castelli is exploited instead of the sphere of influence, so that a WSB trajectory appears to be divided into the three legs: departing, exterior, and arriving. The exterior leg, calculated in the planar four-body model, should be smoothly patched with the departing and arriving legs designed in the Earth-Moon three-body system. Numerical results for the problem of low-energy transfer to the Lunar Gateway resonant near-rectilinear halo orbit show that the adaptation to the ephemeris model is regular and straightforward, with no ad hoc intermediate steps.

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* Junior Researcher, Space Systems Dynamics Department, Keldysh Institute of Applied Mathematics, 4 Miusskaya Sq., 125047 Moscow, Russia.
† Senior Researcher, Space Systems Dynamics Department, Keldysh Institute of Applied Mathematics, 4 Miusskaya Sq., 125047 Moscow, Russia.
‡ Senior Researcher, Space Systems Dynamics Department, Keldysh Institute of Applied Mathematics, 4 Miusskaya Sq., 125047 Moscow, Russia.

AAS 20-702

# LOW ENERGY CAPTURE INTO HIGH INCLINATION ORBITS FOR OCEAN WORLDS MISSIONS

Jared T. Blanchard,* Brian D. Anderson,† Martin W. Lo,‡ and Sigrid Close§

NASA has great interest in developing deep space missions to several of the moons of the outer planets. Jupiter's moon Europa, where evidence points to the existence of a vast subsurface ocean, is especially intriguing. The Europa Lander study aims to determine the feasibility of a robotic mission to this ocean world with the express goal to search for signs of life. Such missions to deep space have tight constraints on mass, and any savings in fuel can be used for scientific instrumentation. Mission designers are focusing on low-energy trajectories to reach the surface of Europa in a fuel-efficient manner. According to NASA scientists, some of the most interesting landing locations are likely found at higher latitudes. This study investigates the possibility of reaching high latitudes of Europa, showing that ballistic trajectories to such regions are sparse. Methods for finding and following these trajectories are explored.

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* Graduate Student, Department of Aeronautics and Astronautics, Stanford University, Stanford, CA 94305, USA. E-mail: jared711@stanford.edu.

† Mission Design Engineer, Outer Planets Mission Design Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. E-mail: brian.d.anderson@jpl.nasa.gov.

‡ Principal Engineer, Outer Planets Mission Design Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. E-mail: martin.w.lo@jpl.nasa.gov.

§ Associate Professor, Department of Aeronautics and Astronautics, Stanford University, Stanford, CA 94305, USA. E-mail: sigridc@stanford.edu.

**AAS 20-726**

# A TIME REGULARIZATION SCHEME FOR SPACECRAFT TRAJECTORIES SUBJECT TO MULTI-BODY GRAVITY

**James Leith[*] and Ryan P. Russell[†]**

A time regularization scheme is introduced that facilitates trajectory optimization in multi-body regimes. The time transformation function enables fixed-step propagation, eliminates the need for multiple models in patched conic approaches, and mitigates the risk of stepping over unplanned flybys. The scheme is motivated by Sundman's two-body regularization, but accounts for multiple bodies using their spheres of influence and a Heaviside approximation. The time transformation enables efficient discretization of the many types of motion that exist in multiple-body regimes. The new formulation is analyzed in several restricted three-body dynamical problems, which serve as proxy models that capture the dominant features of N-body ephemeris models within the solar system. The parameters of the new transformation are tuned, and the performance is compared against several existing regularizations on a diverse set of examples including periodic orbits in the Earth-Moon and Saturn-Enceladus systems, a low-thrust Earth-Moon spiral, and a low-altitude Jupiter-Europa flyby. The transformation is shown to be robust to the differing conditions, outperforming the benchmarks over wide ranges of the tuning parameters. A general set of recommendations for parameter and design variable selection is developed based on the results, and reported at the end of the paper. In the context of spacecraft trajectory design, the transformation is particularly well-suited for trajectories that traverse multiple levels of the sun-planet-moon solar system hierarchy.

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[*] Graduate Student, University of Texas at Austin, 2617 Wichita St., Austin, TX 78712, USA.
E-mail: leithjames01@gmail.com.
[†] Associate Professor, University of Texas at Austin, 2617 Wichita St., Austin, TX 78712, USA.
E-mail: ryan.russell@austin.utexas.edu.

**AAS 20-733**

# TO URANUS WITH LOW THRUST AND GRAVITY ASSIST

**Burhani M. Burhani,* Roberto Flores,† and Elena Fantino‡**

Our knowledge about Uranus and its moons is scarce. To gain insight into the features of this planet and its satellites, an exploration mission is needed. Uranus axial tilt of 98º requires a prohibitive amount of propellant for insertion into an equatorial orbit. To minimize the cost of the orbit insertion maneuver, a combination of low thrust (LT) propulsion and gravity assist (GA) at Jupiter is explored. GA is applied at Jupiter en route to Uranus followed by a LT control strategy that reduces the inclination of the relative velocity respect to Uranus' equator. Preliminary results show that it is possible to eliminate the plane-change maneuver upon arrival at Uranus at the cost of longer transfer time.

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* Ph.D. Student, Department of Aerospace Engineering, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates. E-mail: 100052952@ku.ac.ae.
† Research Scientist, Department of Aerospace Engineering, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates and Associate Professor, Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), 08034 Barcelona, Spain. E-mail: rflores@cimne.upc.edu.
‡ Assistant Professor, Department of Aerospace Engineering, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates. E-mail: elena.fantino@ku.ac.ae.

# SOLAR SYSTEM ESCAPE TRAJECTORIES USING OUTER PLANETARY GRAVITY ASSISTS

**Rohan Patel,[*] Damon Landau,[†] and Try Lam[‡]**

A broad search of outer planet gravity assist sequences reveals flyby conditions that are naturally amenable for solar system escape. The optimal flyby conditions depend on the arrival velocity at the final body and provide the maximum possible escape speed for purely ballistic sequences. Trajectories in the 2030-2060 time frame are categorized by their encounter year with an emphasis on solar system escape speed and direction. All resulting sequences require a Jupiter gravity assist, and a considerable increase in escape speed is found in trajectories that utilize an additional Saturn, Uranus, or Neptune flyby. However, these solutions are limited by their availability and range of right ascensions. All cataloged trajectories are able to escape the solar system at least 3 au/year, and the highest energy sequences are in excess of 5.5 au/year. The search space is then used to find outer planet gravity assist trajectories to Kuiper Belt Objects (KBOs), and several cases are optimized.

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[*] Undergraduate Student, Aerospace Engineering, Cal Poly Pomona, 3801 W Temple Ave., Pomona, California 91786, USA.

[†] Mission Formulation Engineer, Systems Engineering Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA.

[‡] Mission Design Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA.

**AAS 20-749**

# MINIMUM-FUEL LOW-THRUST TRAJECTORY OPTIMIZATION USING TRIGONOMETRIC-BASED REGULARIZATION

**Ehsan Taheri*** **and Kshitij Mall†**

A trigonometric-based regularization technique is proposed for generating fuel-optimal low-thrust trajectories. For a spacecraft equipped with a constant specific impulse and constant maximum-thrust engine, thrust magnitude profile exhibits non-smooth, bang-off-bang structures. The number (and time instant) of switches between thrust and coast arcs and the time duration of these arcs are not known in advance. Regularization and smoothing of bang-bang or bang-off-bang control structures alleviates some of the difficulties in solving a large class of optimal control problems. The capability of the proposed regularization technique is demonstrated through handling state-path constraints (e.g., on the minimum distance from the Sun) on the heliocentric phase of an Earth-to-Mars trajectory.

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* Assistant Professor, Department of Aerospace Engineering, Auburn University, AL 36849, USA.
† Post Doctoral Research Fellow, Department of Aerospace Engineering, Auburn University, AL 36849, USA.

**AAS 20-753**

# REACHABILITY MAPS GENERATION FOR OPPORTUNISTIC TARGETS INTERCEPTION FROM CIS-LUNAR ORBITS

**Lorenzo Colaninno,[*] Stefano Di Marco,[†] Paolo Minacapilli,[‡] Giacomo Petrucci,[§] Andrea Pasquale,[**] and Michèle Lavagna[††]**

Timely interception of interesting small bodies, not easily detectable quite in advance to properly prepare a space mission, still represents a bottleneck in visiting transient pristine comets and deflecting dangerous asteroids. The paper proposes a methodology to rank the celestial sphere zones in terms of reachability, having, among the control variables, the departure orbit as well; the possibility to park in cis-lunar environment, ready to depart as soon as a relevant target is detected is here supposed. Performances involved in the transfer that mostly influence preliminary mission analysis are clustered in a ranking index to support the decision making process.

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[*] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[†] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[‡] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[§] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[**] PhD Candidate, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[††] Full Professor, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.

AAS 20-760

# MAGELLANO: A NAVIGATION AND DATA RELAY CONSTELLATION TO SERVE MARS SURFACE AND SPACE ASSETS

**Marzio Agistri,[*] Alberto Chiaradia,[†] Lyle Campbell,[‡] Adriano Filippo Inno,[§] and Michèle Lavagna[**]**

Upcoming and future missions to Mars will generate rapidly increasing amounts of scientific data and require greater independence from Earth. Therefore, locally provided positioning, navigation, and data transfer services will be critical for any long term exploration plan. Local provision of accurate real-time positioning and high data-rate communications will allow spacecraft to dedicate a greater proportion of their mass and power budgets to payloads, improving science return and cost effectiveness. The design of a suitable constellation is presented here, as well as a strategy for the interplanetary transfer, Mars capture, and achievement of the operational configuration.

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[*] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[†] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[‡] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[§] Master Student, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.
[**] Full Professor, Aerospace Science & Technology Dept., Politecnico di Milano, Italy.