NEW MEXICO EPSCOR

PROXIMITY OPERATIONS FOR NEAR EARTH ASTEROID EXPLORATION

Grant number: NNX11AQ35A

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Sep. 1, 2011-Aug. 31, 2015

Final Report

September 1, 2015

Proximity Operations for Near Earth Asteroid Exploration

New Mexico EPSCoR

Final Report

Narrative Summary: *Research Accomplishments Measured Against the Proposed Goals and Objectives*

Goal 1: Develop strategies to plan trajectories and maneuvers of single or multiple spacecraft to enable NEA missions, including approach and orbital operations, descent, landing and surface operations, and autonomous guidance, navigation, and control capabilities.
Accomplishments for Goal #1: Research has been continued on developing methods and analyses to support close proximity operations about asteroids. With past support of this grant, a variety of approaches were considered and begun. At least two of these were transitioned to funded proposals from the NASA NSTRF program.

Goal 2: Study the impacts of communications and networking constraints within the framework of various protocols on NEA missions, and how such constraints affect and are affected by the trajectories of a constellation of spacecraft at a NEA system.
Accomplishments for Goal #2: Using asteroid orbital simulation models originally designed by project co-PI Scheeres and implemented in Matlab by student Thomas Critz working under the direction of project technical lead Butcher, we have analyzed and quantified the communication tradeoffs associated with operating in the vicinity of various near-earth asteroids. In particular, we have analyzed the data rates and required data buffer sizes for communications between a single orbiting spacecraft and remote sensor platforms placed at various locations on the surface of the asteroid. We have also studied and characterized the problem of determining the position of the orbiting spacecraft relative to those of a set of surface probes using trilateration.

Goal 3: Improve the gravity field modeling of select NEAs through new observations and the development of numerical modeling algorithms, for the purpose of more effective proximity operation modeling and design for robotic and human NEA mission targets.

Accomplishments for Goal #3: Over the course of this grant Co-I Klinglesmith and his students have continued to observe and publish asteroid light curves. Thirty four referred papers have been submitted and accepted for publication in the Minor Planet Bulletin. A total of 108 asteroids have been observed. Ninety six of these asteroids had not had a period determination. The other 12 had known periods and were observed to help determine the asteroid shapes. Two of the published papers presented preliminary shape models that would allow the estimation of gravity fields.

In addition, student Rob Wausson at NMSU, working under the direction of co-PIs Creusere and Butcher, has been comparing the use of the extended Kalman filter to that of the unscented Kalman filter for the purpose of precise estimation of the spacecraft's orbital position. Such precise estimates, when combined with the orbital models developed by co-PI Scheeres, are required for the purposes of estimating asteroid characteristics like mass, density, and nonuniformities.

Research by Co-I Sanyal has significantly improved the understanding of how the weak gravity field of a NEA can lead to a strong interaction and coupling between the rotational (attitude) and translational (orbital) motions of a spacecraft in proximity to the NEA. This research has also shown the necessity of having more accurate dynamics models for the spacecraft in proximity to the NEA, which also gives an improved gravity model for the NEA as predicted by Co-I Sanyal's research the previous year. This is a valuable addition to research started the previous, in which Co-I Sanyal obtained state estimators for spacecraft in proximity to NEA that could also estimate the NEA's gravity parameters; the attitude-orbit coupling in the dynamics of the spacecraft was included in this estimation scheme. Continuing work will consider other improvements to the dynamics model of spacecraft-NEA pairs, like improved and more accurate solar radiation models than the "flat plate" models currently in use by the research community.

Goal 4: Contribute to and promote the development of research infrastructure in New Mexico in areas of strategic importance to the NASA mission while assessing and leveraging the many existing core capabilities relative to NASA in the state.
Accomplishments for Goal #4: co-PI Butcher developed a state-of-the-art orbital mechanics 3D visualization laboratory which is funded by his recent grant from AFOSR (see below). This laboratory will be used for the current project as well as serving as an outreach tool for visiting K-12 students at New Mexico State University.

Goal 5: Improve the capability of New Mexico to gain support from sources outside the NASA EPSCoR program in space and aerospace related STEM-related research.
Accomplishments for Goal #5: Co-I Sanyal has a number of publications that have appeared, are in press, or in review (see list below) that detail the far-reaching and often surprising findings of this research. In addition, he has submitted one NSTRF proposal and one NIAC proposal to NASA over the past year, both of which were turned down. Both proposals were on relative motion estimation of observed space objects (which may be NEAs or other natural or artificial objects), using vision-based and inertial sensors onboard a spacecraft in proximity. While Co-I Sanyal does not plan to submit another proposal to the NSTRF program (mainly because he does not currently have any US citizen or permanent resident student that could be supported by this program), he plans to submit proposals to the NIAC program as well as the Small Spacecraft Technology program in the coming year. In addition, Co-I Sanyal was also a Co-PI in a DURIP instrumentation proposal to DoD with Dr. Ou Ma of the MAE department as the PI.

Goal 6: Develop partnerships between NASA research assets and New Mexico academic institutions, federal laboratories, and industry.

Accomplishments for Goal #6: Co-I Sanyal made one research presentation at NASA Ames in October 2013 and will make another research presentation at NASA Langley in July 2014. In addition, he chaired and co-organized a tutorial session with Dr. Suresh Joshi of NASA Langley at the American Control Conference in Portland this year (June 4-6, 2014). The topic of this session was Rendezvous, Proximity and Capture of Space Objects; it featured Co-I Scheeres as the lead presenter, and had two presentations from NASA Langley and industry on the Asteroid Retrieval and Redirect Mission (ARRM). During Co-I Sanyal's to NASA Langley in mid-July this year, he will also present his research findings in front of an audience consisting of leading NASA researchers and industry partners working on the ARRM. While a permanent faculty at the University of Arizona, Dr. Butcher was accepted into the Air Force Research Laboratory (AFRL) Summer Faculty Fellowship Program (SFFP) and spent the summer of 2015 working in the Space Vehicles Directorate of AFRL at Kirtland AFB in Albuquerque, NM under the direction of Dr. T. Alan Lovell. In addition, Dr. Butcher was recently funded through a grant from AFRL (with Dr. Lovell as the technical POC) to do research related to nonlinear spacecraft relative motion.

Goal 7: Contribute to New Mexico's overall research infrastructure, science and technology capabilities, higher education, and/or economic development.
Accomplishments for Goal #7: The first Ph.D. graduate in aerospace engineering at NMSU (Dr. Morad Nazari) recently defended and graduated in Dec. 2013. Dr. Butcher, who taught AE 562 Astrodynamics for the second time in Fall 2013, was Dr. Nazari's advisor. The second Ph.D. student in aerospace engineering at NMSU, Ehsan Samiei, successfully defended his dissertation in March 2015. He was co-advised by Dr. Butcher and Dr. Sanyal. Dr. Sanyal's aerospace engineering Ph.D. student Jan Bohn recently successfully passed the comprehensive exam and expects to defend his Ph.D. dissertation in January 2016. Two M.S. students who were supported by this project, Thomas Critz (advised by Dr. Butcher) and Robert Wauson (co-advised by Dr. Creusere and Dr. Butcher), should soon complete their degrees.

Goal 8: Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) to improve the environment for STEM education in New Mexico.
Accomplishments for Goal #8: On a yearly basis CO-I Klinglesmith and the New Mexico Tech Astronomy Club sponsored about 35 star parties per year at the Etscorn Campus Observatory. They averaged 1500 people per year, mainly young students, who attended the star parties. Klinglesmith taught an "Optical Astronomy for Teachers" for the New Mexico Tech's "Teacher's Master of Science" program in the summer of 2013. It was attended by 5 teachers. He also taught an "Astronomy Laboratory, PHY327-328 for New Mexico Tech undergraduates in the 2013 -2014 school year. One of the NMT astronomy club members, Veronica Pierce tutored home schooled elementary students in Astronomy and Physics in the Spring of 2014.

Supplementary Documentation: ***The Research***

Goal 1: Develop strategies to plan trajectories and maneuvers of single or multiple spacecraft to enable NEA missions, including approach and orbital operations, descent, landing and surface operations, and autonomous guidance, navigation, and control capabilities.

With respect to Goal #1, major accomplishments are summarized as follows:

1. Efficient ways to automatically map out the forward sets of a spacecraft given a certain level of control authority. By developing such maps an autonomous mission planner can make informed decisions on what courses of control action will yield the best outcome. Past supported student David Surovik, currently funded by an NSTRF grant.
2. Stability of spacecraft motion in relatively distant orbits about small asteroids and comets. Coupled effects of asteroid gravitational attraction and solar gravity and radiation pressure perturbations can cause both stable and unstable motions to exist. Deeper understanding of these dynamics is lacking, and has been a focus of research. Past supported student Samantha Rieger, currently funded by an NSTRF grant to pursue this work.
3. Ballistic deployment of science packages to the surfaces of asteroids has been studied. This is a refinement of a previously developed concept for asteroid exploration. Currently funded students Simon Tardivel and Stefaan Van wal are currently supported for this work. Tardivel has recently defended his PhD.

During the course this project, Co-I Sanyal made significant advances in understanding the dynamics of asteroids and of spacecraft in proximity to a NEA, as well as guidance, navigation and control of such spacecraft. Research on the dynamics of spacecraft near rotating asteroids led Co-I Sanyal to some surprising discoveries on the effects of gravity-induced dynamical coupling between the attitude and translational (orbital) dynamics on the spacecraft's motion. Probably the most important finding is that the "point mass model" for a spacecraft that is much smaller and much less massive than the NEA it is exploring, is completely wrong in predicting the trajectory of the spacecraft. Considering that this "point mass model" has been the mainstay of the research community engaged in asteroid/comet exploration, the implications of this research finding are far-reaching and transformative. Numerical simulations with accurate dynamics models have shown that the trajectories of a micro-spacecraft (around 50 kg) modeled as a point mass versus a rigid body spacecraft are significantly different around NEAs like Toutatis (mass of order 10^{13} kg), Itokawa and Bennu (masses of order 10^{11} kg). Moreover, these significant differences arise in a time period of a few hours to a few days, not weeks or months! These results are depicted in the figures below. In addition to the significant findings on translation-rotation (or orbit-attitude) coupling of spacecraft motion in proximity to NEAs, Co-I Sanyal has developed a dynamics model-free state estimation scheme using onboard vision-based and inertial sensors, which can be used for estimating the motion states of a NEA as observed from a spacecraft in proximity. The first publication on this estimation scheme applied to NEA was accepted for publication in Advances in Space Research (see under published journal articles). The first publication on this estimation framework for (relative) attitude estimation, appeared in fall 2014 in the journal

Automatica. Automatica is the flagship journal of the International Federation for Automatic Control (IFAC) and is the highest impact journal on control theory and applications worldwide, with an impact factor of 3.1.

Future work will consider utilizing the attitude-orbit coupling to control the orbital trajectories of spacecraft exploring NEA using propellant-less attitude control only. This concept was proposed in response to the NASA Innovative Advanced Concepts (NIAC) program in fall 2014, and it made it into the second round of reviews where it was not passed. A revised version will be proposed in fall 2015, in collaboration with NASA Langley Research Center.

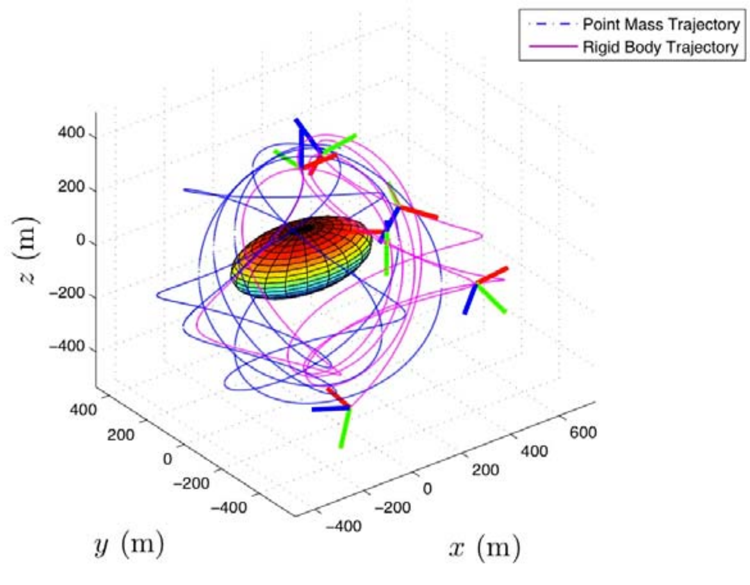

Figure 1. Differences between point mass and rigid body trajectories for a 63 kg spacecraft in proximity to an ellipsoid with mass and size similar to NEA Itokawa (simulated time period is 3700 s).

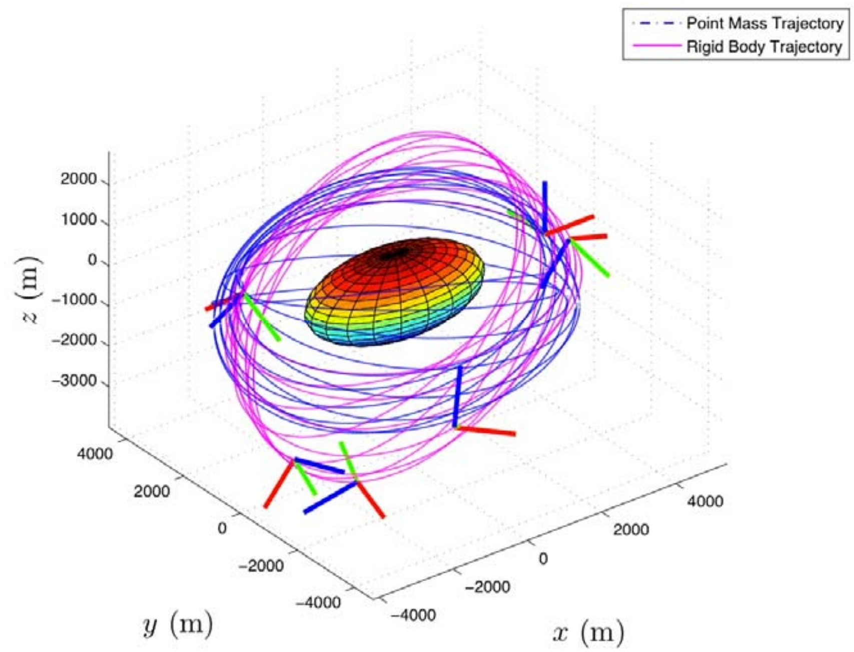

Figure 2. Differences between point mass and rigid body trajectories for a 63 kg spacecraft in proximity to an ellipsoid with mass and size similar to NEA Toutatis (simulated time period is 3 days).

Goal 2: Study the impacts of communications and networking constraints within the framework of various protocols on NEA missions, and how such constraints affect and are affected by the trajectories of a constellation of spacecraft at a NEA system.

Our specific accomplishments with respect to this Goal include using asteroid orbital simulation models originally designed by project co-PI Scheeres and implemented in Matlab by student Thomas Critz working under the direction of project technical lead Butcher to analyze and quantify the communication tradeoffs associated with operating in the vicinity of various near-earth asteroids. One focus was on the data rates and required data buffer sizes for communications between a single orbiting spacecraft and remote sensor platforms placed at various locations on the surface of the asteroid. The assumption here is that the spacecraft is required to act is a relay for data being collected by the surface platforms so that this data can either be shared amongst the platforms for local collaborative processing or transmitted back to earth. This thrust illustrates what one might call the 'best case' communications scenario: if an unobstructed line of sight exists between a surface platform and the spacecraft, we assume that reliable communication is possible at some fixed bit rate. In a real system, line of sight is necessary for reliable communication (at all radio frequencies that are practical for space communications, at least), but it is not sufficient to guarantee error-free reception. In general, one must also consider the signal to noise ratio (SNR) of the system. Calculating the SNR requires information about the antennas and modulation hardware as well as RF background noise models (which depends not only on the antenna selection but also on the positions of the surface and space platforms). We incorporated such models into our current simulator.

We have also studied the problem of simultaneously estimating the relative positions of the orbiting spacecraft and the surface probes using the only the communications signals. This can be viewed as an inverted GPS-type solution. There is an added complexity, however, in that the surface probes do not have high precision clocks, so round-trip flight times must be used. Once again, the triaxial ellipsoid model of Scheeres is used here. For solving the resulting trialateration equations, we have considered and are analyzing in detail both a linear and a nonlinear approach. Multiple papers based on this work have appeared in the Proceedings of the International Telemetering Conference as well as the Procceedings of the 2015 IEEE Aerospace Conference.

<u>Goal 3</u>: Improve the gravity field modeling of select NEAs through new observations and the development of numerical modeling algorithms, for the purpose of more effective proximity operation modeling and design for robotic and human NEA mission targets.

Over the course of this grant Co-I Klinglesmith and his students have observed and published numerous asteroid light curves. Thirty-four referred papers have been submitted and accepted for publication in the Minor Planet Bulletin. A total of 108 asteroids have been observed. 96 of the asteroids had not had a period determination. The other 12 had known periods and were observed to help determine the asteroid shapes. In addition two preliminary shape models were published. This effort will allow the estimation of gravity fields.

Furthermore, student Rob Wausson at NMSU, working under the direction of co-PIs Creusere and Butcher, has been comparing the use of the extended Kalman filter to that of the unscented Kalman filter for the purpose of precise estimation of the spacecraft's orbital position. Such precise estimates, when combined with the orbital models developed by co-PI Scheeres, are required for the purposes of estimating asteroid characteristics like mass, density, and nonuniformities.

Finally, research by Co-I Sanyal has significantly improved the understanding of how the weak gravity field of a NEA can lead to a strong interaction and coupling between the rotational (attitude) and translational (orbital) motions of a spacecraft in proximity to the NEA. This research has also shown the necessity of considering this coupling in the dynamics of spacecraft in proximity to the NEA in order to estimate accurately the gravity parameters for the NEA, and was presented at the AAS/AIAA Space Flight Mechanics meeting in January 2014. This is a valuable addition to research started earlier during this project, in which Co-I Sanyal obtained state estimators for spacecraft in proximity to NEA that could also estimate the NEA's gravity parameters; the attitude-orbit coupling in the dynamics of the spacecraft was included in this estimation scheme. Continuing work which appeared in Advances in Space Research in July 2015, considers other improvements to the dynamics model of spacecraft-NEA pairs, like improved and more accurate solar radiation models than the "flat plate" models currently in use by the research community.

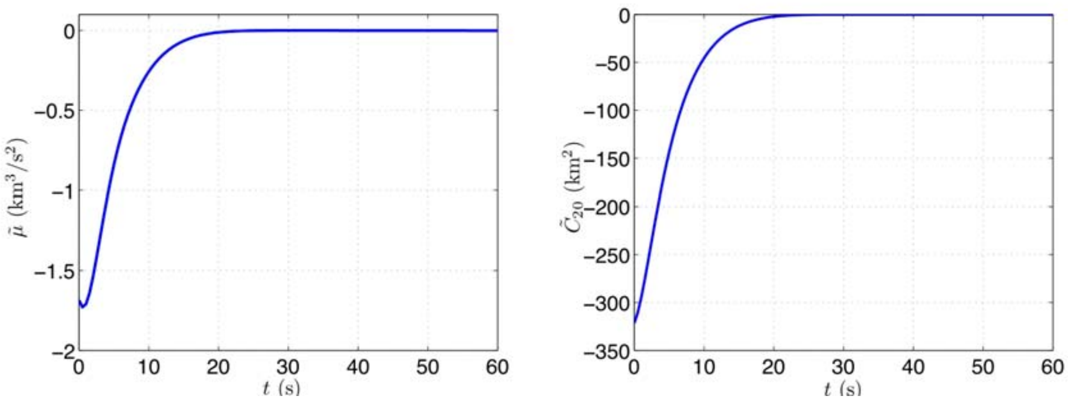

Figure 3. Numerical simulation results showing time evolution of estimation errors for first and one of the second order gravity coefficients of an asteroid the size of Mathilde, obtained from remote measurements by an orbiting spacecraft.

Goal 4: Contribute to and promote the development of research infrastructure in New Mexico in areas of strategic importance to the NASA mission while assessing and leveraging the many existing core capabilities relative to NASA in the state.

During the course of this project,_ co-PI Butcher developed a state-of-the-art orbital mechanics 3D visualization laboratory which is funded by his recent grant from AFOSR (see below). This laboratory will be used for the current project as well as serving as an outreach tool for visiting K-12 students at New Mexico State University. Since Drs. Butcher and Sayal have left NMSU for faculty positions outside of the state, it is hoped that new faculty recruited by the NMSU College of Engineering will take over this facility and continue to expand its capabilities.

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Supplementary Documentation: *Participants*

Faculty

Dr. Eric A. Butcher, New Mexico State University/University of Arizona
Dr. Amit K. Sanyal, New Mexico State University
Dr. Charles D. Creusere, New Mexico State University
Dr. Daniel J. Scheeres, University of Colorado Boulder
Dr. Daniel A. Klinglesmith III, New Mexico Institute of Mining and Technology

Post-doctoral, graduate, and undergraduate students supported from EPSCoR funds

Dr. Daero Lee, postdoc, New Mexico State University
Evan Nelson, Ph.D. student, New Mexico State University
Thomas Critz, M.S. student, New Mexico State University
Robert Wauson, M.S. student, New Mexico State University
Ethan Risley, undergraduate, New Mexico Institute of Mining and Technology
Janek Turk, undergraduate, Mexico Institute of Mining and Technology
Angelica Vargas, undergraduate, Mexico Institute of Mining and Technology
Simon Tardivel, Ph.D. student, University of Colorado
Stefaan Van wal, Ph.D. student, University of Colorado
Jan Bohn, PhD student, New Mexico State University
Maziar Izadi, PhD student, New Mexico State University
Sashi Vishwanathan, PhD student, New Mexico State University
Austin Dehart, undergraduate, New Mexico Institute of Mining and Technology
Gaurav Misra, MS student, New Mexico State University

Curtis Warren, undergraduate, New Mexico Institute of Mining and Technology

Students working on aspects of current project who are supported through other sources
Morad Nazari, Ph.D. student, New Mexico State University
Ehsan Samiai, Ph.D. student, New Mexico State University
Lee Holguin, M.S. student, New Mexico State University
Sashi Vishwanathan, M.S. student, New Mexico State University
Jan Bohn, M.S. student, New Mexico State University
Erik Komendera, Ph.D. student, University of Colorado
David Surovik, Ph.D. student, University of Colorado
Samantha Rieger, Ph.D. student, University of Colorado
Jesse Hanowell, undergraduate, New Mexico Institute of Mining and Technology
Karl Madden, undergraduate, New Mexico Institute of Mining and Technology
Samual Montgomery, undergraduate, New Mexico Institute of Mining and Technology

Supplementary Documentation: *Systematic Change*

Systemic change as evidenced by:

Improvements in jurisdiction research and development infrastructure: *See accomplishments for Goal #4 above.*

Increased financial commitment from the jurisdiction, industry, and participating institutions: *None*

Response of activities to NASA and jurisdiction priorities: *None*

Reordered jurisdiction and/or institutional priorities: *None*

Supplementary Documentation: *Collaborations*

NASA interactions:

- Telecon with Dr. Shyam Bhaskaran of NASA/JPL in Dec. 2013.

- Dr. Butcher visited AFRL and gave a guest talk in July 2013, and his student William Anthony spent his second summer as a AFRL Space Scholar working with Dr. Lovell of AFRL.

Other federal Agencies: *None*

Other academic institutions: *none outside of project collaborators*

Supplementary Documentation: ***Space Grant Interaction***

New Mexico Space Grant provided funding to Dr. Amit Sanyal, including for curriculum development in aerospace engineering at the undergraduate level. (This resulted in his teaching Spacecraft Attitude Dynamics and Controls in the Spring 2012 semester.)

Supplementary Documentation: ***Technology Transfer***

Examples of successful technology transfer to the private sector: *None*

Patents awarded or applied for:

Title: High Control Authority Variable Speed Control Moment Gyroscope Date submitted: January 26, 2015; application number 14/605,935 Authors: Amit Sanyal and Sasi Prabhakaran Viswanathan

Supplementary Documentation: ***Publications and Presentations***

Peer-Reviewed Conference Papers presented:

J. Bohn and A. Sanyal, ``Unscented State Estimation for Rigid Body Motion on SE(3)," IEEE Conference on Decision and Control, Maui, HI, pp. 7498-7503, Dec 2012.

D. Lee, S. P. Viswanathan, L. Holguin, A. K. Sanyal and E. A. Butcher, ``Decentralized Guidance and Control for Spacecraft Formation Flying Using Virtual Leader Configuration," American Control Conference, Washington DC, pp. 4833-4838, June 2013.

M. Sorgenfrei, A. K. Sanyal and S. Joshi, ``On the Performance of a Genetic Algorithm for Spacecraft Controller Gain Optimization," AIAA Guidance, Navigation and Control Conference, Boston, MA, Aug 2013, AIAA-2013-5029.

S. P. Viswanathan, A. K. Sanyal, F. Leve, and N. H. McClamroch, ``Geometric Approach to Attitude Dynamics and Control of Spacecraft with Variable Speed Control Moment Gyroscopes," IEEE Multi-Conference on Systems and Control, Hyderabad, India, pp. 556-561, Aug 2013.

M. Izadi, J. Bohn, D. Lee, A. K. Sanyal, E. Butcher, and D. J. Scheeres ``A Nonlinear Observer Design for a Rigid Body in the Proximity of a Spherical Asteroid,” ASME Dynamic Systems and Control Conference, Oct 21-23, 2013, Stanford, CA.

S. Bras, M. Izadi, C. Silvestre, A. Sanyal and P. Oliveira, ``Nonlinear Observer for 3D

Rigid Body Motion," IEEE Conference on Decision and Control, Florence, Italy, Dec 2013.

A. K. Sanyal, J. Bohn and A. M. Bloch, ``Almost Global Finite-time Stabilization of Rigid Body Attitude Dynamics," IEEE Conference on Decision and Control, Florence, Italy, Dec 2013.

S. Prabhakaran, A. K. Sanyal and F. Leve, ``A General Dynamics Model for Spacecraft with Variable Speed Control Moment Gyroscopes," AIAA/AAS Space Flight Mechanics Meeting, Santa Fe, NM, Jan 2014.

D. Lee, A. K. Sanyal, E. A. Butcher, and D. J. Scheeres, ``Finite-time Observer for Rigid Spacecraft Motion over an Asteroid," AIAA/AAS Space Flight Mechanics Meeting, Santa Fe, NM, Jan 2014.

D. Lee, A. K. Sanyal, E. A. Butcher, and D. J. Scheeres, ``Finite-time Control for Body-fixed Hovering of Rigid Spacecraft over an Asteroid," AIAA/AAS Space Flight Mechanics Meeting, Santa Fe, NM, Jan 2014.

J. Bohn and A. Sanyal, ``Almost Global Finite-Time Stable Observer for Rigid Body Attitude Dynamics," American Control Conference, Portland, OR, pp. 4949-4954, June 2014.

A. Sanyal, E. Butcher and M. Izadi, ``Determination of Relative Motion of a Space Object from Simultaneous Measurements of Range and Range Rate," American Control Conference, Portland, OR, pp. 1607-1612, June 2014.

A. Sanyal, M. Izadi, G. Misra, E. Samiei and D. Scheeres, ``Estimation of Dynamics of Space Objects from Visual Feedback during Proximity Operations", SPACE 2014, San Diego, CA, August 2014.

A. K. Sanyal, M. Izadi and J. Bohn, ``An Observer for Rigid Body Motion with Almost Global Finite-time Convergence", ASME Dynamic Systems and Control Conference, San Antonio, TX, October 2014.

G. Misra and A. Sanyal, ``Analysis of Orbit-Attitude Coupling of Spacecraft Near Small Solar System Bodies", AIAA Guidance, Navigation and Control Conference, Kissimmee, FL, January 2015.

S. P. Viswanathan, A. Sanyal and M. Izadi, ``Mechatronics Architecture of Smartphone-Based Spacecraft ADCS using VSCMG Actuators", Indian Control Conference, Chennai, India, pp. 310-315, January 2015.

E. Samiei, A. K. Sanyal, and E. A. Butcher, ``Asymptotic Stabilization of Rigid Body Attitude Motion in the Presence of Unknown Time Delay in Feedback", Indian Control Conference, Chennai, India, pp. 209-214, January 2015.

G. Misra, A. Sanyal and E. Samiei, ``Asteroid Landing Guidance Design in the Framework of Coupled Orbit-Attitude Spacecraft Dynamics," AIAA/AAS Space Flight Mechanics Meeting, Williamsburg, VA, January 2015.

M. Izadi, E. Samiei, A. K. Sanyal and V. Kumar, ``Comparison of an Attitude Estimator based on the Lagrange-d'Alembert Principle with some State-of-the-Art Filters," IEEE International Conference on Robotics and Automation, Seattle, WA, May 2015.

E. Samiei, M. Izadi, S. P. Viswanathan, A. K. Sanyal, and E. A. Butcher, ``Robust Stabilization of Rigid Body Attitude Motion in the Presence of a Stochastic Input Torque," IEEE International Conference on Robotics and Automation, Seattle, WA, May 2015.

K. Sreenath and A. K. Sanyal, ``The Reaction Mass Biped: Equations of Motion, Hybrid Model for Walking and Trajectory Tracking Control," IEEE International Conference on Robotics and Automation, Seattle, WA, May 2015.

Creusere, C. ,Nelson, E., Critz, T., Butcher, E.; "Analysis of communication interconnectedness in the proximity of near-earth asteroids," *Proc. International Telemetering Conference*, San Diego, CA, October 2012.

Nelson, E., Creusere, C., Critz, T., Butcher, E.; "Analysis of communication rates in the proximity of near-earth asteroids," *Proc. International Telemetering Conference*, Las Vegas, NV, October 2013.

Nelson, E., Creusere, C, Butcher, E.; "Determination of position around near-earth asteroids using communication relays," *Proc. International Telemetering Conference*, San Diego, CA, October 2014.

Nelson, Evan; Creusere, Charles D.; Butcher, Eric, "Determining position around an asteroid using communication relays and trilateration," *Aerospace Conference, 2015 IEEE* , vol., no., pp.1,6, 7-14 March 2015; doi: 10.1109/AERO.2015.7118955

<u>Articles submitted to or published in refereed journals</u>

A. K. Sanyal and N. Nordkvist, ``Attitude State Estimation with Multi-Rate Measurements for Almost Global Attitude Feedback Tracking," AIAA Journal of Guidance, Control and Dynamics, vol. 35(3), pp. 868-880, 2012.

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