NEW MEXICO EPSCOR

PROXIMITY OPERATIONS FOR

NEAR EARTH ASTEROID EXPLORATION

Grant number: NNX11AQ35A

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Progress Report: Year 3

July 2, 2014

Proximity Operations for Near Earth Asteroid Exploration

New Mexico EPSCoR

Progress Report: Year 3

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.
Progress on 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.

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.

The last year of research on this project by Co-I Sanyal was a very productive year, based on both the number of results obtained as well as their significance. 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 of this research project 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 and 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 relative pose of a NEA as observed from a spacecraft in proximity. The first publication on this scheme, for (relative) attitude estimation, was recently accepted in the journal Automatica, which is the flagship journal of the International Federation for Automatic Control (IFAC) and is the highest impact journal on controls worldwide, with an impact factor of 3.9. Recently (early June) Co-I Sanyal presented these research findings at the American Control Conference in a tutorial session he co-organized with Dr. Suresh Joshi of NASA Langley; this session featured two talks from NASA researchers engaged in the Asteroid Redirect and Retrieval Mission (ARRM).

Future work will consider utilizing the attitude-orbit coupling to control the orbital trajectories of spacecraft exploring NEA using propellant-less attitude control only.

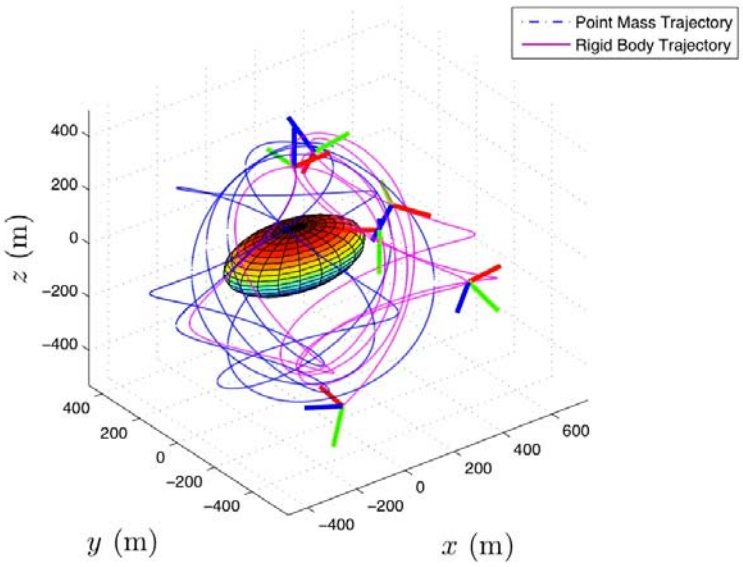

Figure 1. Differences between point mass and rigid body trajectories for a 63 kg spacecraft in proximity to an ellipsoid with mass and size similar to NEA Itokawa (simulated time period is 3700 s).

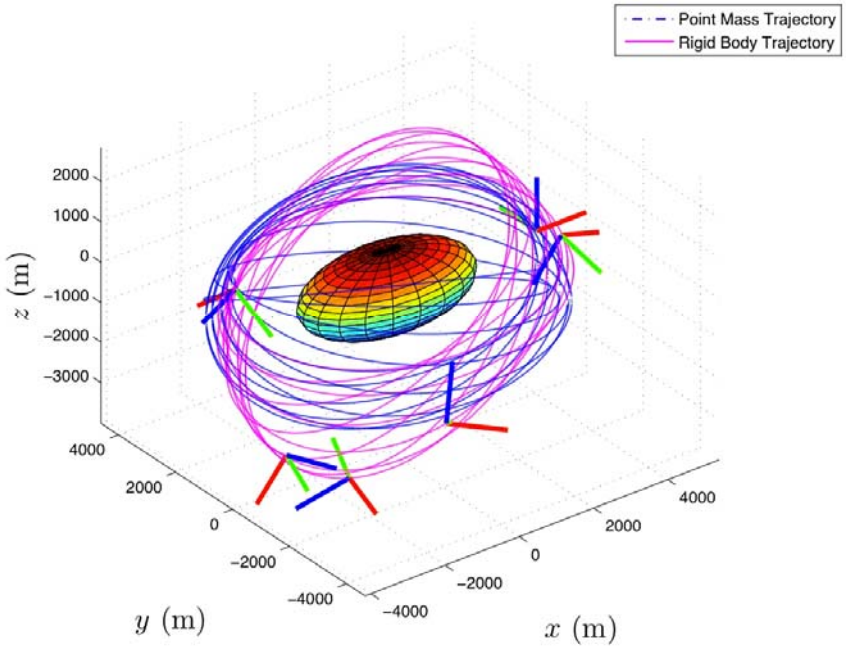

Figure 2. Differences between point mass and rigid body trajectories for a 63 kg spacecraft in proximity to an ellipsoid with mass and size similar to NEA Toutatis (simulated time period is 3 days).

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.

Progress on Goal #2: We continue to move forward on the tasks associated with this project Goal which is described as follows in the proposal. Specifically, 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 continued to analyze and quantify the communication tradeoffs associated with operating in the vicinity of various near-earth asteroids. Last year our 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 have actually incorporated such models into our current simulator, but we have not yet performed extensive case studies or Monte Carlo analysis with the resulting system.

Based on discussions amongst our team, a new major focus in the reporting year has been on the problem of simultaneously estimating the relative positions of the orbiting spacecraft and the surface probes using 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. A paper based on this work will appear at the International Telemetering Conference in October, and we are also currently working on a submission to the 2015 IEEE Aerospace Conference.

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.

Progress on Goal #3: During the third year of this grant Co-I Klinglesmith and his students have continued to observe and publish asteroid light curves. Ten referred papers have been submitted and accepted for publication in the Minor Planet Bulletin. A total of 44 asteroids have been observed. Thirty two 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, 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.

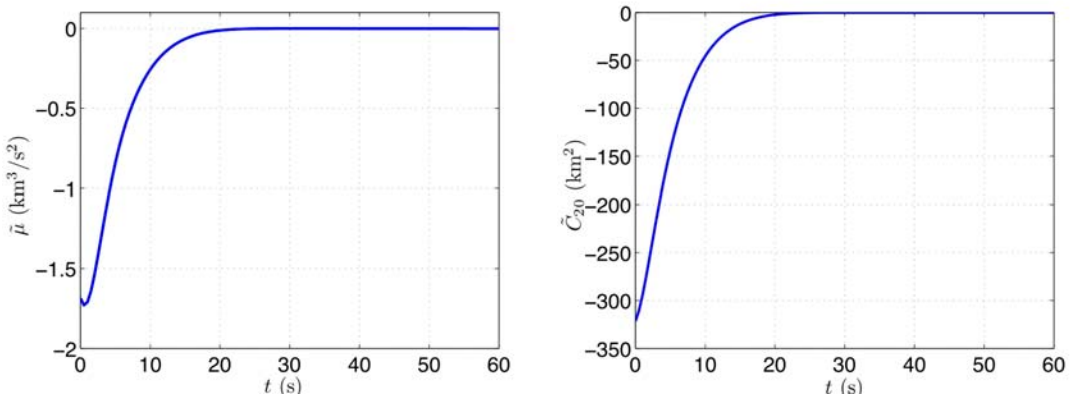

Figure 3. Numerical simulation results showing time evolution of estimation errors for first and one of the second order gravity coefficients of an asteroid the size of Mathilde, obtained from remote measurements by an orbiting spacecraft.

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.
Progress on 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. With the departure of co-PI Butcher to the University of Arizona, it is expected that co-PI Sayal will take over this lab.

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.
Progress on 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.
Progress on 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.

Goal 7: Contribute to New Mexico's overall research infrastructure, science and technology capabilities, higher education, and/or economic development.
Progress on Goal #7: The first Ph.D. graduate in aerospace engineering at NMSU (Dr. Morad Nazari) recently defended and graduated in Dec. 2013. Dr. Butcher taught AE 562 Astrodynamics for the second time in Fall 2013. The second PhD student in aerospace engineering at NMSU, Ehsan Samiei, is expected to defend his dissertation in Fall 2014.

Goal 8: Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) to improve the environment for STEM education in New Mexico.
Progress on Goal #8: CO-I Klinglesmith and the New Mexico Tech Astronomy Club sponsored 36 star parties at the Etscorn Campus Observtory. Over 1500 people, mainly young students 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.

Systemic change as evidenced by:

Improvements in jurisdiction research and development infrastructure: See progress on 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

Examples of successful technology transfer to the private sector: None

Extent to which collaborations with jurisdiction agencies, industry, research and academic institutions, and NASA have evolved.
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.

Discussion of interaction between and cooperation with the jurisdiction's Space Grant Consortium.
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.)

Research success of individual investigators as measured by:

Peer-Reviewed Conference Papers presented:

1) 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, Stanford, CA.

2) 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.

3) 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.

4) 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.

5) 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.

6) 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.

7) J. Bohn and A. Sanyal, ``Almost Global Finite-Time Stable Observer for Rigid Body

Attitude Dynamics," American Control Conference, Portland, OR, June 2014.

8) 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, June 2014.

Articles submitted to or published in refereed journals

Ferrero, A., Klinglesmith, D.A., Pilcher, F., 2014, "The rotation period of 1137 Raissa", Minor Planet Bull., 41-1, 33

Hanowell, J., 2013, "Photometric Analysis of 4611 Vulkaneifel, Minor Planet Bull., 40-3, 157

Klinglesmith, D. A., Hanowell, J., Risley, E., Turk, J., Vargas, A., Warren, C.A., 2013, "Etscorn Observered Asteroids: Results for six Asteroids December 2013 - March 2013, Minor Planet Bull., 40-3, 154-156

Klinglesmith, D. A., Franco, L., (2013), " Lightcurve and H-G Parameters for Asteroid 2007 McCuskey", Minor Planet Bull., 40-3, 177-178

Klinglesmith, D. A., Hanowell, J., Risley, E., Turk, J., Vargas, A., Warren, C.A., 2013, "Inversion Model Candiates", Minor Planet Bull., 40-4, 190-193

Klinglesmith, D. A., Hanowell, J., Risley, E., Turk, J., Vargas, A., Warren, C.A., 2014, "Asteroid Observations at Etscorn: Mid 2013", Minor Planet Bull., 41-1, 15-16

Klinglesmith, D. A., Hanowell, J., Risley, E., Turk, J., Vargas, A., Warren, C.A., 2014, "Asteroid Observations at The Etscorn Campus Observatory", Minor Planet Bull., 41-2, 81-84

Klinglesmith, D. A., Hanowell, J., Risley, E., Turk, J., Vargas, A., Warren, C.A., 2014, "Lightcurves for inversion Model Cadidates", Minor Planet Bull., 41-3

Pilcher, F., Alvarez, E.M., Ferrero, A., Klinglesmith, D.A., Vargas, A., Oey, J., 2014, "Rotation Period Determination for 870 Manto", Minor Planet Bull., 70

Pilcher, F., Benishek, V., Ferrero, A., Klinglesmith, D. A., Pravec, P., Roy, R., Behrend, R., 2013, "New Photometry of 1473 Ounas", Minor Planet Bull., 40-3, 126-129

Nazari, M., Wauson, R., Critz, T., Butcher, E.A., and Scheeres, D.J., "Observer-Based Body-Frame Hovering Control over a Tumbling Asteroid," *Acta Astronautica*, in press (2014).

Lee, D., Bang, H., Butcher, E. A., and Sanyal, A. K., "Kinematically Coupled Relative Spacecraft Motion Control using State-Dependent Riccati Equation Method," ASCE *Journal of Aerospace Engineering*, in press (2014).

Lee, D., Bang, H., Butcher, E. A., and Sanyal, A. K., "Nonlinear Output Tracking and Disturbance Rejection for Autonomous Close Range Rendezvous and Docking of Spacecraft," *Transactions of the Japan Society for Aeronautical and Space Sciences*, in press (2014).

Lee, D., Sanyal, A., K., and Butcher, E. A., "Asymptotic Tracking Control for Spacecraft Formation Flying with Decentralized Collision Avoidance," *Journal of Guidance, Control, and Dynamics*, doi: 10.2514/1.G000101 (2014).

Nazari, M. and Butcher, E. A., "Fuel Efficient Periodic Gain Control Strategies for Spacecraft Relative Motion in Elliptic Chief Orbits," *International Journal of Dynamics and Control*, submitted.

Lee, D., Sanyal, A. K., Butcher, E. A., and Scheeres, D. J., "Finite-Time Control for Spacecraft Body-Fixed Hovering over an Asteroid," *Transactions on Aerospace and Electronic Systems*, revision submitted.

D. Lee, A. Sanyal and E. Butcher, ``Asymptotic Tracking Control for Spacecraft Formation Flying with Decentralized Collision Avoidance," to appear in AIAA Journal of Guidance, Control and Dynamics, 2014.

A. K. Sanyal and A. Goswami, ``Dynamics and Balance Control of the Reaction Mass Pendulum (RMP): A 3D Multibody Pendulum with Variable Body Inertia," ASME Journal of Dynamic Systems, Measurement and Control, vol. 136(2), paper 021002, 2014.

Lee, D., Butcher, E.A., and Sanyal, A. K., "Sliding Mode Control on SE(3) for Decentralized Spacecraft Formation Flying with Collision Avoidance," *Aerospace Science and Technology*, submitted.

S. Tardivel, D.J. Scheeres, P. Michel, S. Van wal, Sanchez. “Surface Motion on an Asteroid,” submitted to Journal of Spacecraft and Rockets, 1/2014.

S. Tardivel, P. Michel, and D.J. Scheeres. 2013. “Deployment of a lander on the binary asteroid (175706) 1996 FG3, potential target of the european MarcoPolo-R sample return mission,” Acta Astronautica 89: 60-70.

A. Weiss, I. Kolmanovsky, D. S. Bernstein, and A. Sanyal, ``Inertia-Free Spacecraft Attitude Control Using Reaction Wheels," AIAA Journal of Guidance, Control and Dynamics, vol. 36(5), pp. 1425-1439, 2013.

M. Izadi and A. K. Sanyal, ``Rigid Body Attitude Estimation Based on the Lagrange-d'Alembert Principle," to appear in Automatica, 2014.

S. Tardivel and D.J. Scheeres. 2013. “Ballistic Deployment of Science Packages on Binary Asteroids,” Journal of Guidance, Control and Dynamics 36(3): 700-709.

E. Komendera, E. Bradley, and D.J. Scheeres. “Efficiently Locating Impact and Escape Scenarios in Spacecraft Reachability Sets,” paper presented at the AIAA/AAS Astrody- namics Specialist Meeting, Minneapolis, August 2012.

D.A. Surovik and D.J. Scheeres. “Computational Efficiency of Symplectic Integrators for Space Debris Orbit Propagation,” paper presented at the AIAA/AAS Astrodynamics Specialist Meeting, Minneapolis, August 2012.

D.A. Surovik and D.J. Scheeres. “Adaptive Envisioning of Reachable Mission Outcomes for Autonomous Navigation at Small Bodies,” paper to be presented at the AAS/AIAA Astrodynamics Specialist Meeting, Hilton Head, South Carolina, August 2013.

E. Komendera, D.J. Scheeres and E. Bradley. “Intelligent Computation of Reachability Sets for Space Missions,” IAAI Conference, 2012.

Talks, presentations, or abstracts at professional meetings

Sanyal, A. K. Izadi, M., and Butcher, E. A., “Determination of Relative Motion of a Space Object from Simultaneous Measurements of Range and Range Rate,” 2014 American Control Conference, June 4-6, 2014, Portland, OR.

Lee, D., Sanyal, A., Butcher, E. A., and Scheeres, D. J., “Finite-Time Control for Body-Fixed Hovering of Rigid Spacecraft Over an Asteroid,” AAS 14-221, 2014 AAS Spaceflight Mechanics Meeting, Jan. 26-30, Santa Fe, NM.

Lee, D., Sanyal, A., Izadi, M., Butcher, E. A., and Scheeres, D. J., "Finite-Time Observer for Rigid Spacecraft Motion Over an Asteroid," AAS 14-260, 2014 AAS Spaceflight Mechanics Meeting, Jan. 26-30, Santa Fe, NM.

Nelson, E., Creusere, C.D., Critz, T., and Butcher, E.A., "Analysis of Communication Rates in the Proximity of Near-Earth Asteroids," Proc. International Telemetering Conference, Las Vegas, NV, Oct. 2013.

Izadi, M., Bohn, J., Lee, D., Sanyal, A.K., Butcher, E. A., and Scheeres, D.J., "A Nonlinear Observer Design for Estimation of the States and the Gravitational Parameter of a Spherical Asteroid," 2013 ASME Dynamical Systems and Control Conference, Oct. 21-23, Palo Alto, CA.

Lee, D., Butcher, E.A., and Sanyal, A., "Sliding Mode Control for Decentralized Spacecraft Formation Flying using Geometric Mechanics," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

Lee, D., Sanyal, A. K., Butcher, E. A., and Scheeres, D. J., "Spacecraft Hovering Control for Body-Fixed Hovering over a Uniformly Rotating Asteroid using Geometric Mechanics," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

Nazari, M., Butcher, E. A., and Mesbahi, A., "On Control of Spacecraft Relative Motion in the Case of an Elliptic Keplerian Chief," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

Nazari, M., Wauson, R., Critz, T., Butcher, E. A., and Scheeres, D. J., "Observer-Based Body-Frame Hovering Control over a Tumbling Asteroid," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

Lee, D., Viswanathan, S., Holguin, L., Sanyal, A.K., and Butcher, E. A., "Decentralized Guidance and Control for Spacecraft Formation Flying using Virtual Target Configuration," 2013 American Control Conference, June 17-19, 2013, Washington, D.C.

Butcher, E., and Nazari, M., "Optimal Control of Spacecraft Motion in Time-Periodic Astrodynamic Systems," extended abstract for 8th European Nonlinear Dynamics Conference, July 6-11, 2014, Vienna.

Butcher, E., "Comparison of Strategies for Control of Time-Periodic Astrodynamic Systems," invited talk at Air Force Research Laboratory, Albuquerque, NM, July 30, 2013.

<u>Articles submitted to NASA venues</u>

Presentation made at NASA Ames by Co-I Sanyal, titled “Robust State and Gravity Estimation of Asteroids from Observations made by Spacecraft in Proximity”, October 2013.

Patents and patent applications

None

Follow-on grant proposals submitted/funded including funding amounts

Amit Sanyal and Eric Butcher, *Robust State and Uncertainty Estimation for Unmanned Systems in the Presence of External Uncertainties*, NSF, $278,158, Sep. 1, 2011-Aug. 30, 2014.

Amit Sanyal and Ou Ma, *A Special Robot and Mobile Platform for Experimental Research on Space Robotics Technology*, AFOSR (DURIP), not funded.

Daniel Scheeres, proposal to NASA NSTRF program on autonomous NEA mission planning, awarded.

Participants

Faculty

Dr. Eric A. Butcher, New Mexico State University
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Post-doctoral, graduate, and undergraduate students supported from EPSCoR funds

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